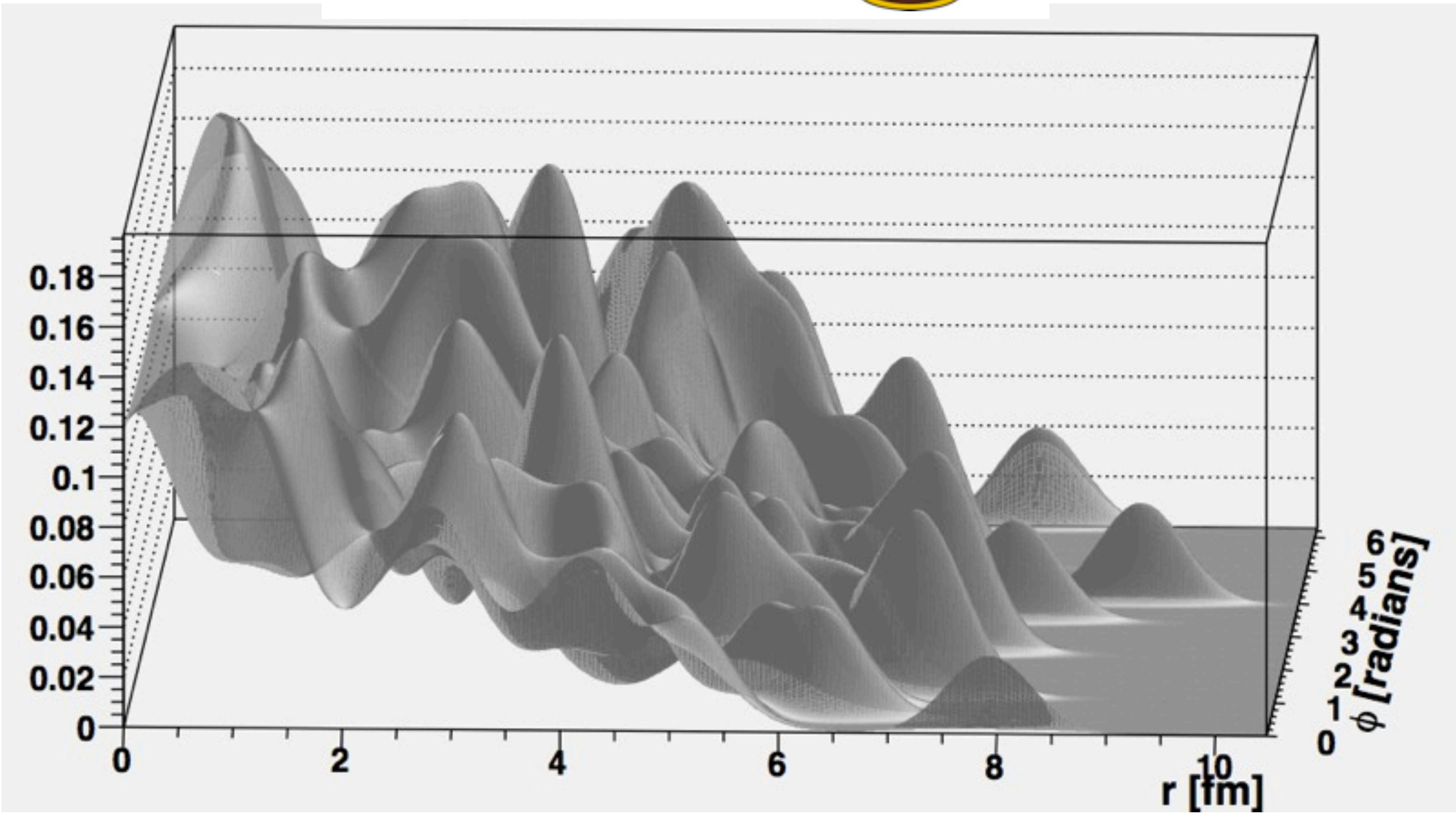
Sartre - A Monte Carlo event generator for diffraction in eA

Calculating the incoherent and total cross-sections in diffractive exclusive vector meson production (and DVCS) in eA

Tobias Toll with T. Ullrich

RIKEN Lunch Seminar

10/27/11



What we want:

To build a Monte Carlo event generator for an EIC

What exists for eA:

DPM-JetIII - not maintained, no diffraction

Diffraction will play a big role in the EIC eA programme.

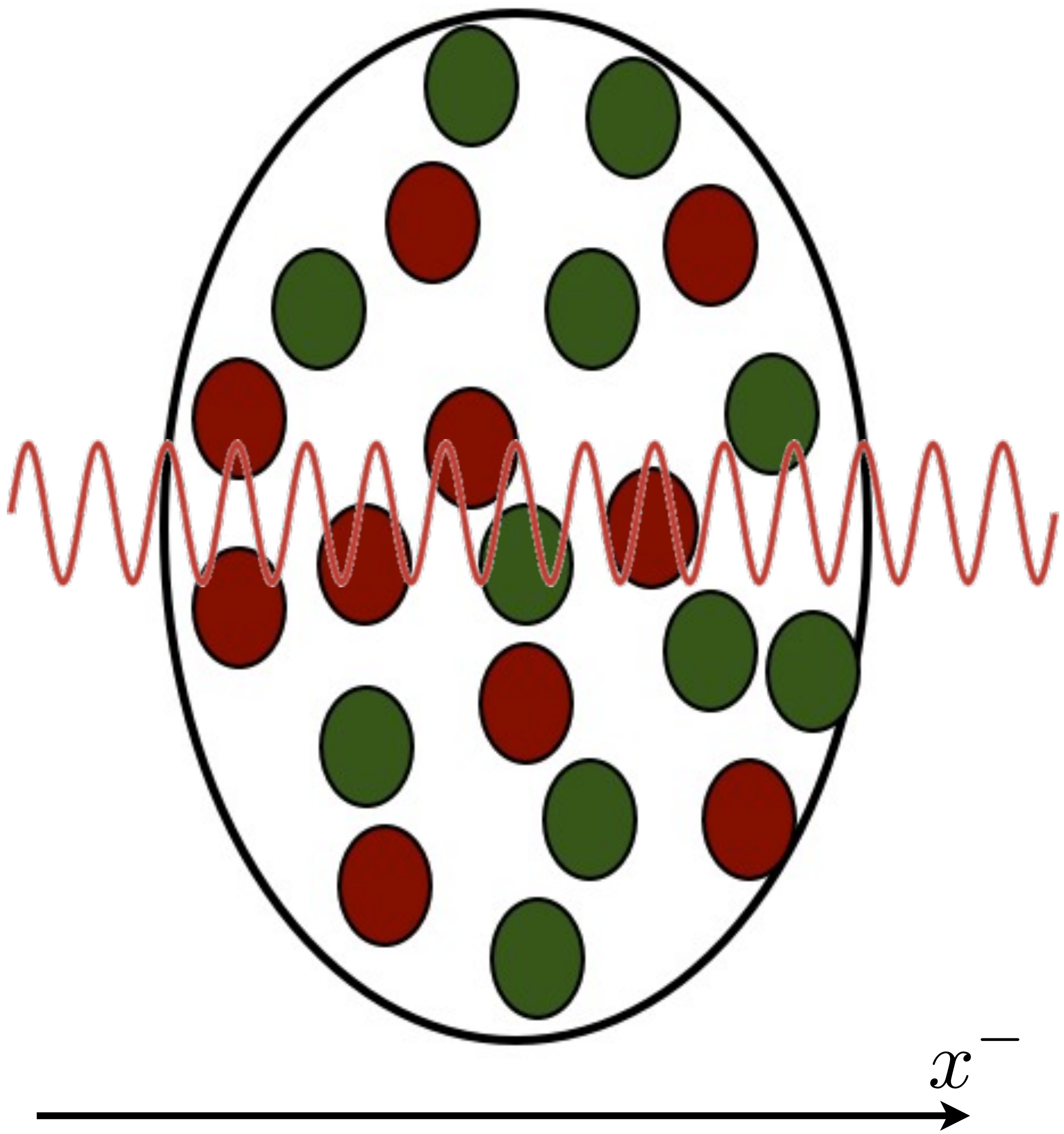
No existing MC event generator for this physics.

e+A Physics Program: Science Matrix

Result of INT workshop in Seattle in fall ’10 (arXiv: 1108.1713)

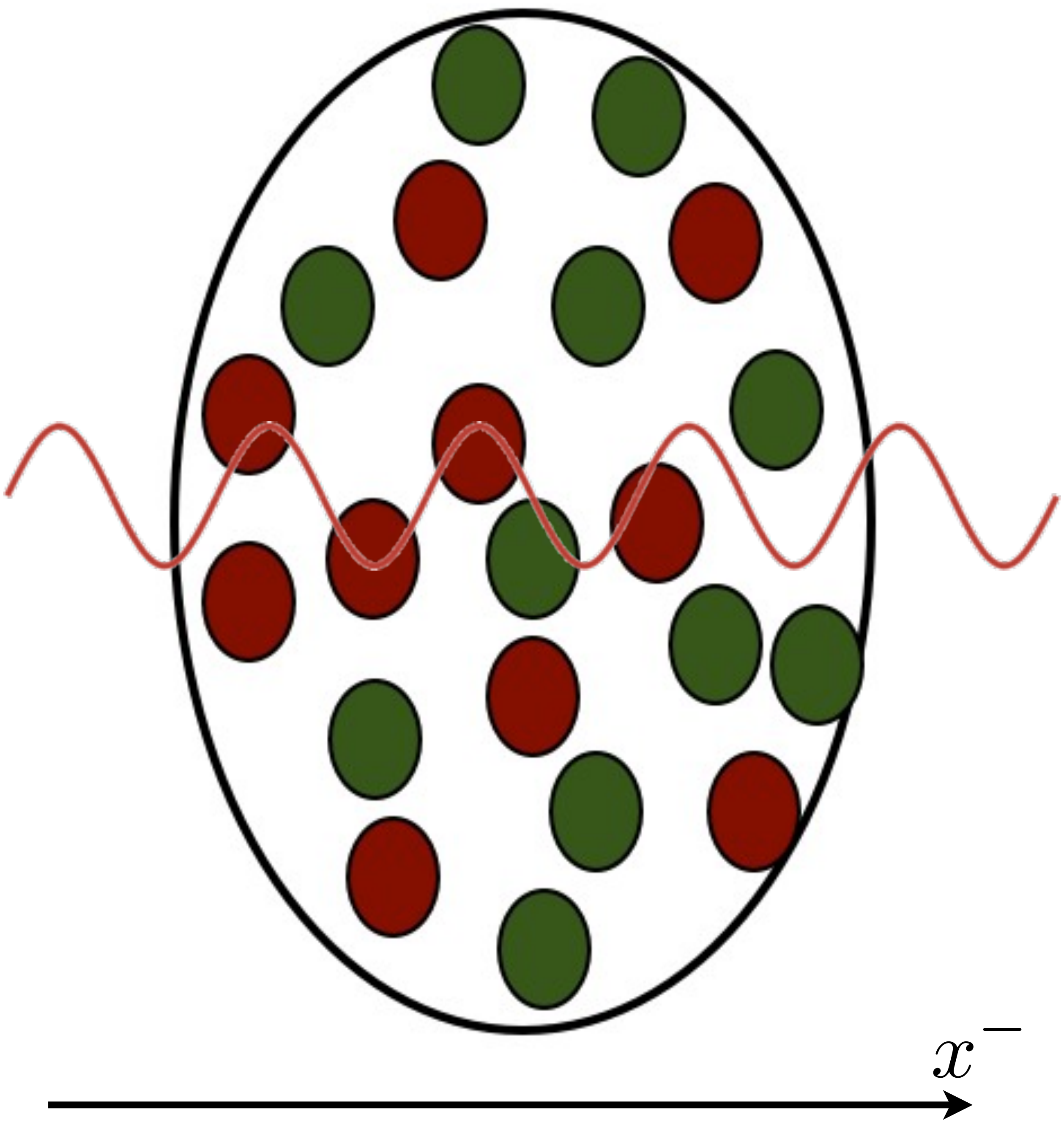
Deliverables	Observables	What we learn	Phase-I	Phase-II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} < x < 1$	saturation regime
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavors and charm; jets	rare probes and bottom; large-x gluons
b dependence of gluon distribution and correlations	Diffractive VM production and DVCS, coherent and incoherent parts	Interplay between small-x evolution and confinement	Moderate x with light and heavy nuclei	Extend to low-x range (saturation region)

Probing the Nucleus at small *x*



At large x: large p^+, short wavelength in x^-, individual nucleons can be resolved.

Probing the Nucleus at small *x*



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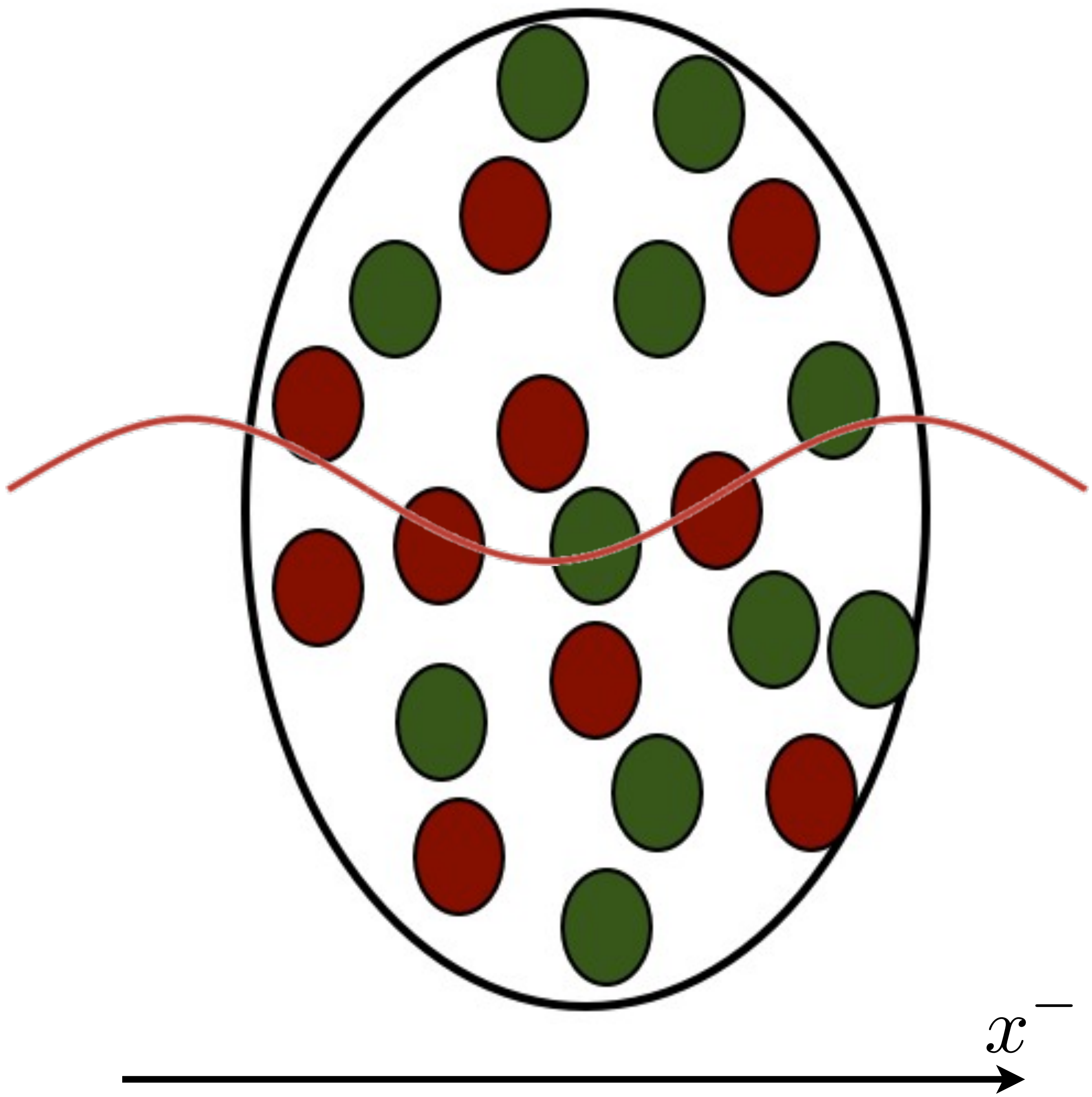
At smaller x,
coherently probe larger area.

Probing the Nucleus at small *x*



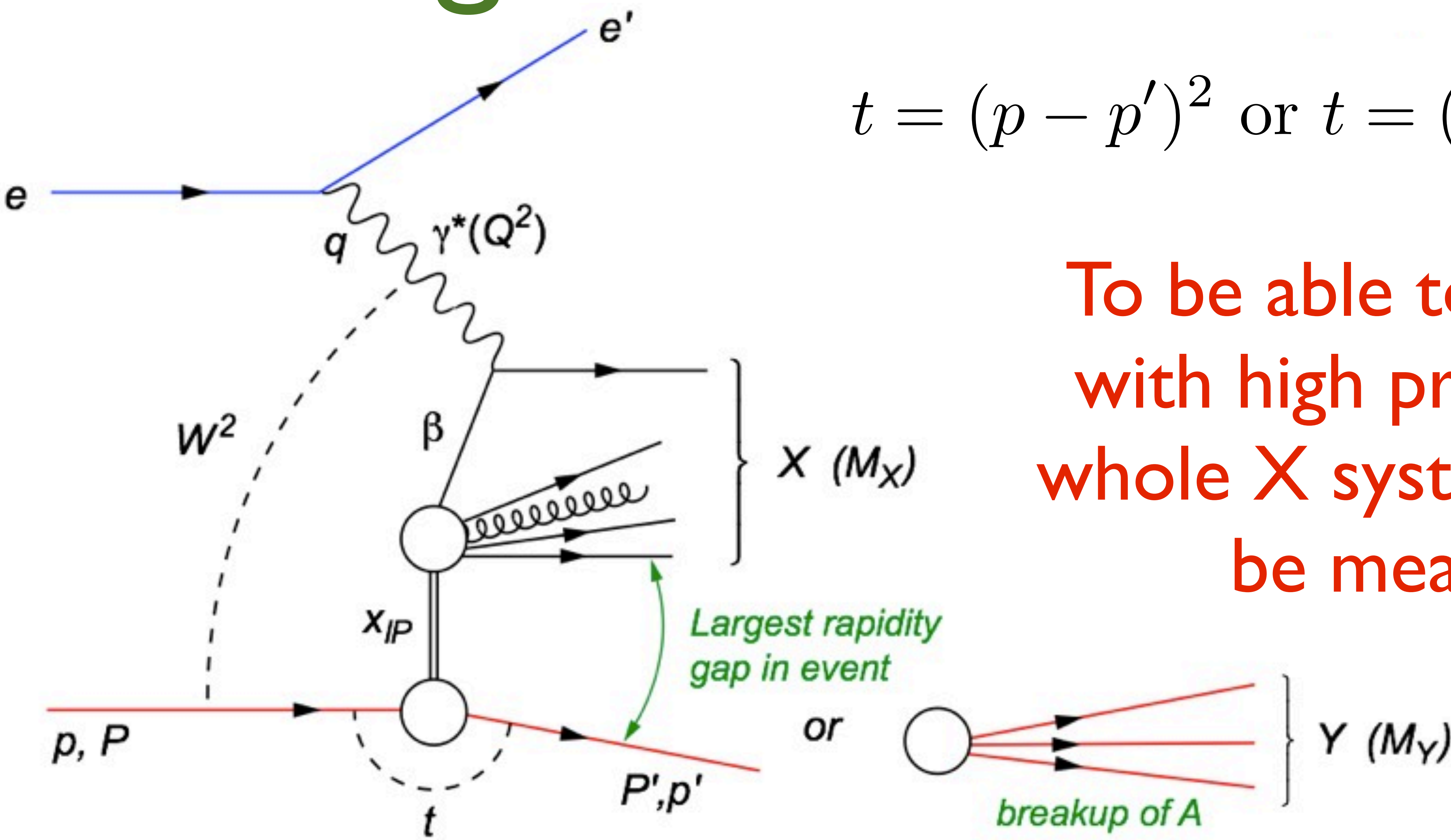
At large x: large p^+, short wavelength in x^-, individual nucleons can be resolved.

At smaller x, coherently probe larger area.

At $x \ll \frac{A^{-1/3}}{M_N R_p}$ coherently probing the whole nucleus.

Challenge for MC, can not just use "A x Pythia"!!

Measuring the b-dependence of gluons in a nucleus



$$t = (p - p')^2 \text{ or } t = (p - Y)^2$$

To be able to measure *t* with high precision, the whole X system needs to be measured.

Can't measure Y well, or p' at all.

Need exclusive diffractive processes: Vector Mesons and DVCS

Measuring the b-dependence of gluons in a nucleus

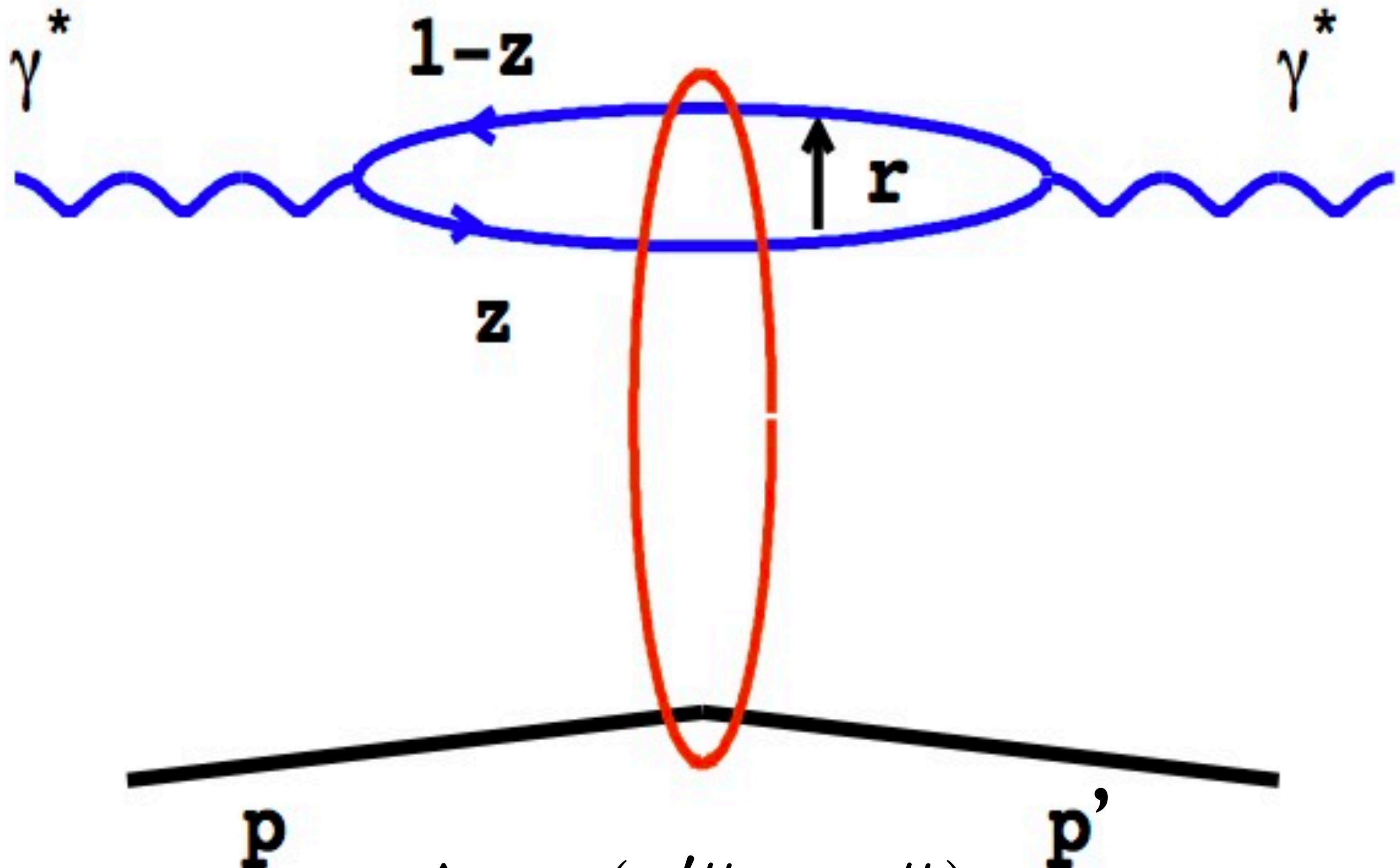
Gluons - small *x*!

The b-dependence is the Fourier conjugate of

$\Delta = \sqrt{-t}$ need to measure the t-distribution!

Start with *ep*

The Dipole Model



Elastic photon-proton scattering

$$\Delta \equiv (p'^{\mu} - p^{\mu})_{\perp}$$

$$\mathcal{A}^{\gamma^* p}(x, Q, \Delta) = \sum_f \sum_{h,\bar{h}} \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \Psi^*_{h\bar{h}}(r, z, Q) \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{h\bar{h}}(r, z, Q)$$

Exclusive diffractive processes at HERA within the dipole picture, H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016, arXiv:hep-ph/0606272v2

The Dipole Model

$$\mathcal{A}^{\gamma^* p}(x,Q,\Delta) = \sum_f \sum_{h,\bar{h}} \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \Psi^*_{h\bar{h}}(r,z,Q) \mathcal{A}_{q\bar{q}}(x,r,\Delta) \Psi_{h\bar{h}}(r,z,Q)$$

Use:

Optical theorem:

$$\mathcal{A}_{q\bar{q}}(x,r,\Delta) = \int \mathrm{d}^2\boldsymbol{b}\, \mathrm{e}^{-\mathrm{i}\boldsymbol{b}\cdot\boldsymbol{\Delta}} \mathcal{A}_{q\bar{q}}(x,r,b) = \mathrm{i} \int \mathrm{d}^2\boldsymbol{b}\, \mathrm{e}^{-\mathrm{i}\boldsymbol{b}\cdot\boldsymbol{\Delta}}\, 2\,[1 - S(x,r,b)]\,.$$

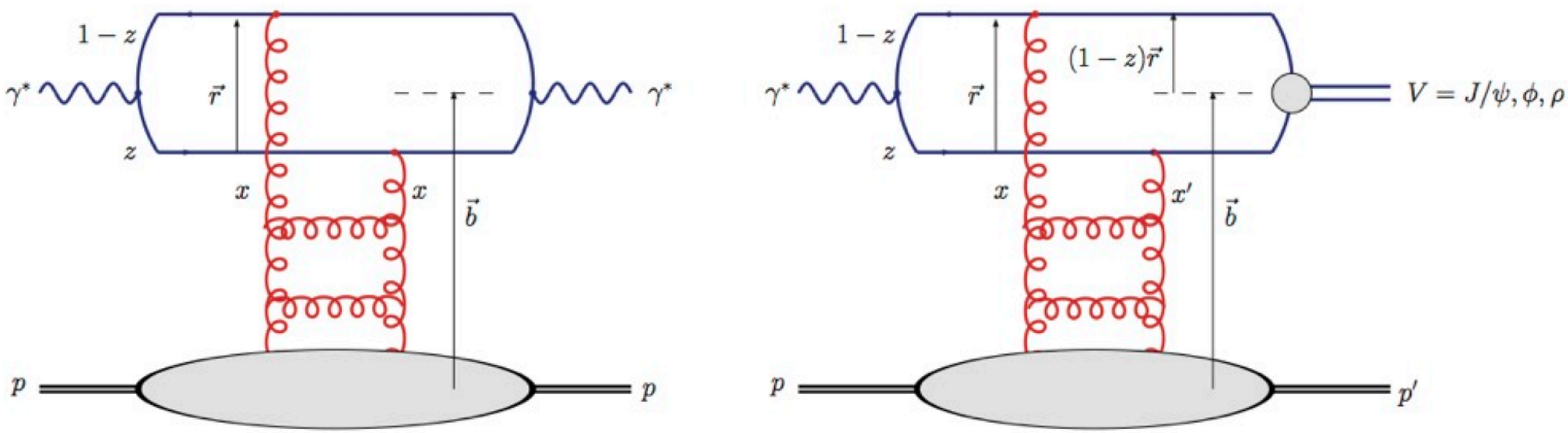
Real Part of S-matrix:

$$\sigma_{q\bar{q}}(x,r) = \mathrm{Im}\,\mathcal{A}_{q\bar{q}}(x,r,\Delta=0) = \int \mathrm{d}^2\boldsymbol{b}\, 2\overbrace{[1 - \mathrm{Re}\, S(x,r,b)]}^{\mathcal{N}(x,r,b)}$$

Define dipole cross-section:

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\mathcal{N}(x,r,b)$$

Vector Meson Production



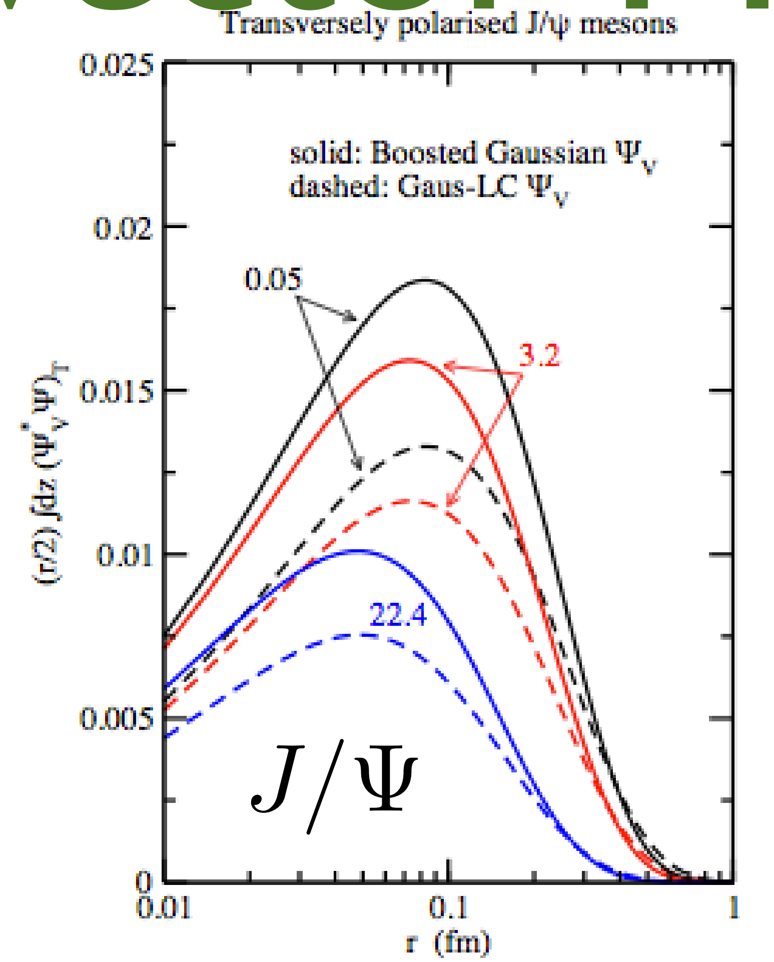
$$\Delta \equiv (p'^{\mu} - p^{\mu})_{\perp}$$

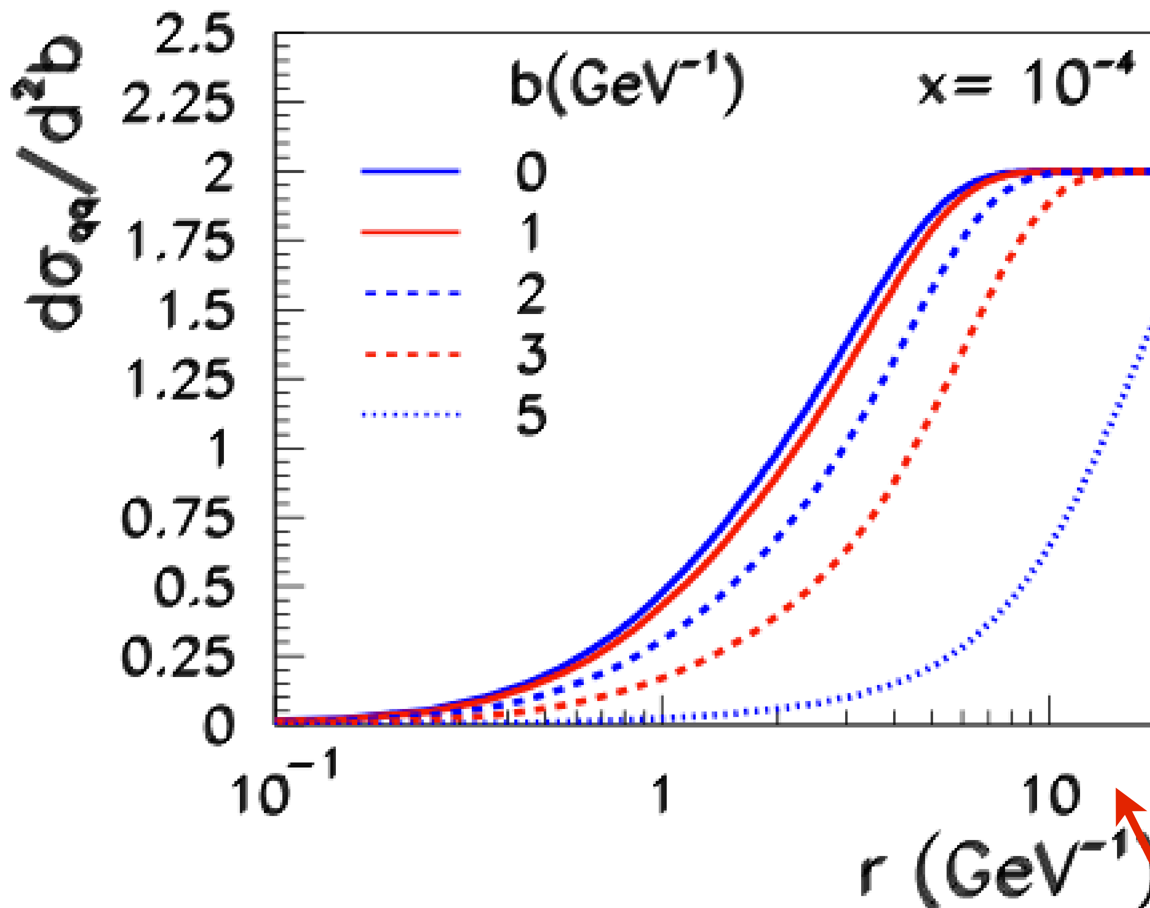
$$\mathcal{A}_{T,L}^{\gamma^* p \to Vp}(x, Q, \Delta) = i \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^* \Psi)_{T,L} e^{-i([1-z]\mathbf{r}+\mathbf{b})\cdot\mathbf{\Delta}} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}$$

"Known from QED"

Needs to be modeled

Vector Meson Production





$$\Delta \equiv (p'^{\mu} - p^{\mu})_{\perp}$$

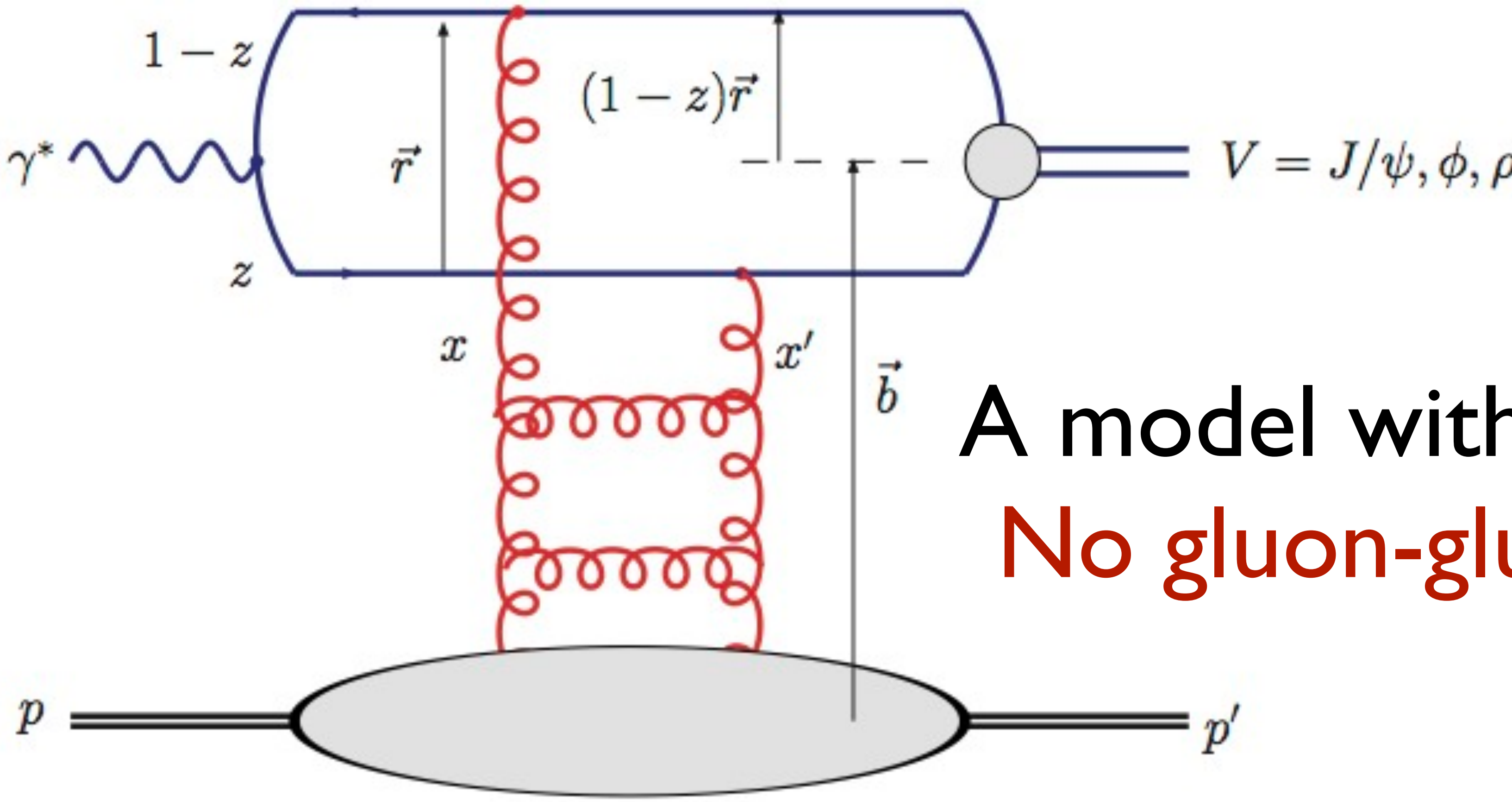
$$\mathcal{A}_{T,L}^{\gamma^* p \to V p}(x, Q, \Delta) =$$

$$i \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^* \Psi)_{T,L} e^{-i([1-z]\mathbf{r}+\mathbf{b})\cdot\mathbf{\Delta}} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}$$

"Known from QED"

Needs to be modeled

The b-Sat Model

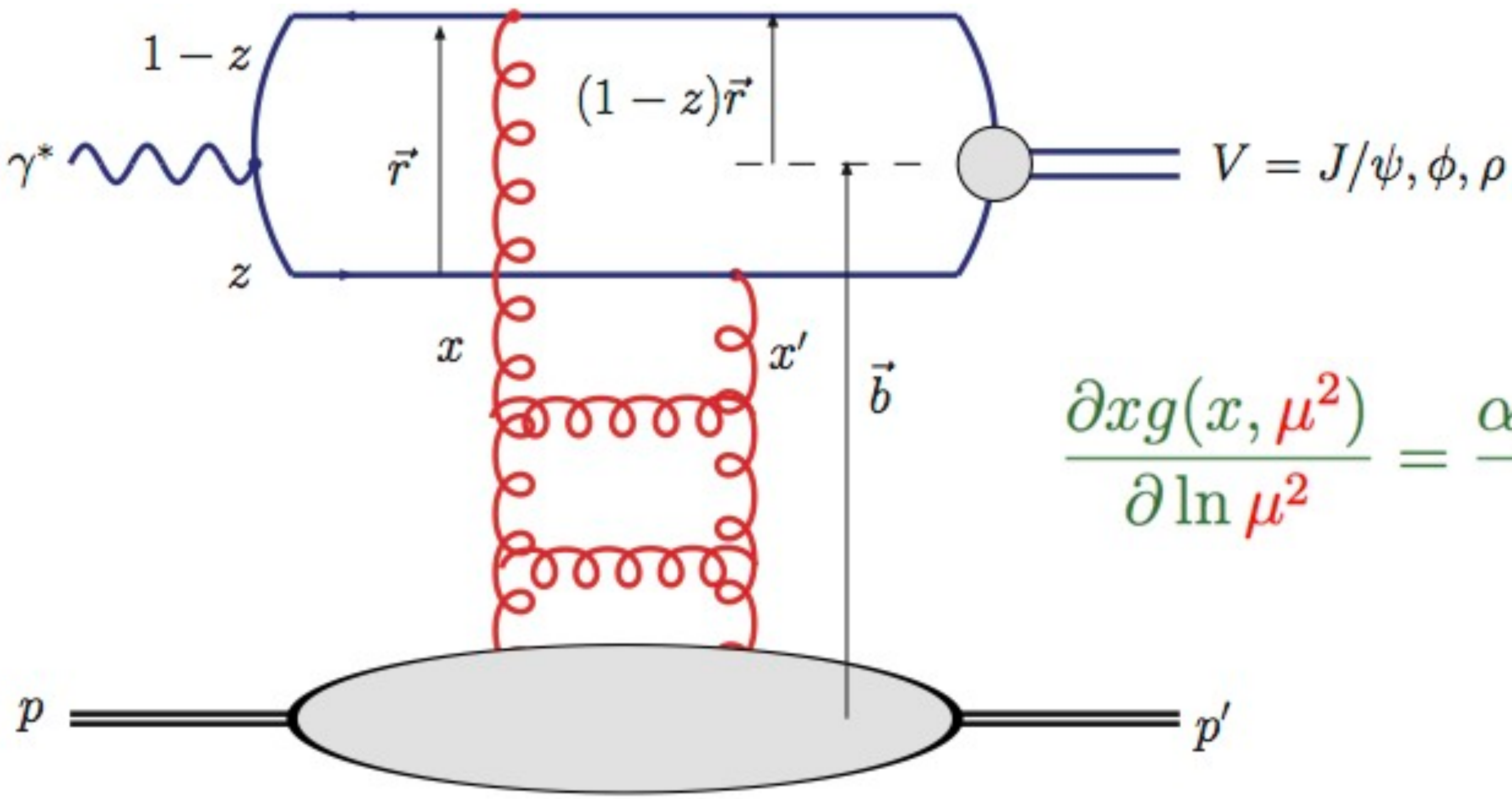


A model with multiple scatterings.

No gluon-gluon recombinations!

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) xg(x,\mu^2) T(b)\right)\right]$$

The b-Sat Model

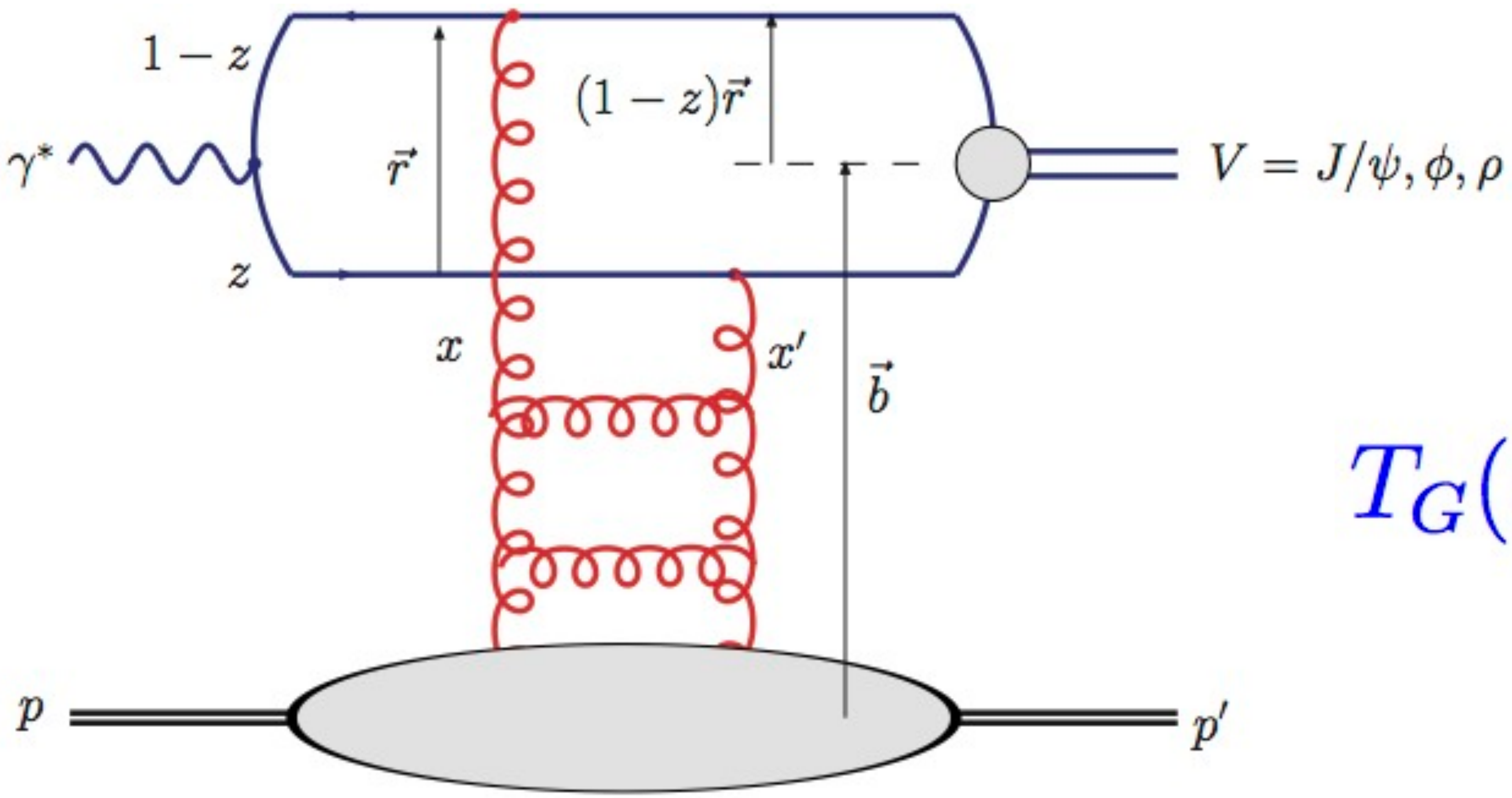


$$\frac{\partial xg(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \mathrm{d}z P_{gg}(z) \frac{x}{z} g\left(\frac{x}{z}, \mu^2\right)$$

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) xg(x,\mu^2) T(b)\right)\right]$$

$$\mu^2 = \frac{4}{r^2} + \mu_0^2$$

The b-Sat Model



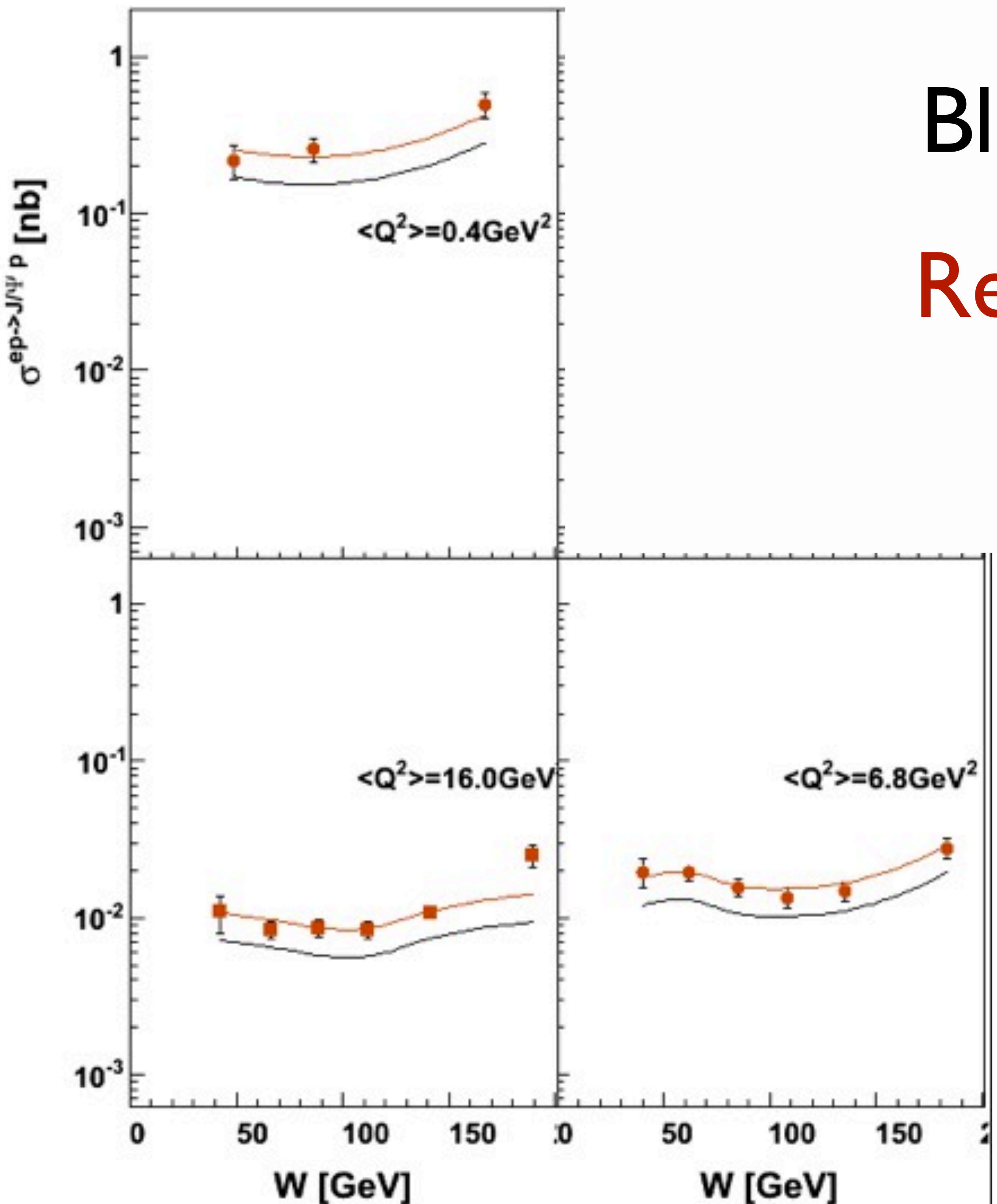
$$T_G(b) = \frac{1}{2\pi B_G} e^{-\frac{b^2}{2B_G}}$$

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) xg(x,\mu^2) T(b)\right)\right]$$

First comparison with data

Previous version of code for *ep*

Exclusive electroproduction of J/Psi mesons at HERA Nuc. Phys. B695



Black Curve: XDVMP b-CGC

Red Curve: Black Curve x 1.5

Something is missing!!

Plots produced by Ramiro Debbe

Real Amplitude Corrections

So far the amplitude has been assumed to be purely imaginary.

To take the Real part of the amplitude into account it can be multiplied by a factor $(1+\beta^2)$

β is the ratio Real/Imaginary parts of the Amplitude:

$$\beta = \tan\left(\lambda\frac{\pi}{2}\right) \qquad \lambda \equiv \frac{\partial \ln\left(\mathcal{A}_{T,L}^{\gamma^* p \to Ep}\right)}{\partial \ln(1/x)}$$

This goes bad for large x~10^{-2}

Real Amplitude Corrections

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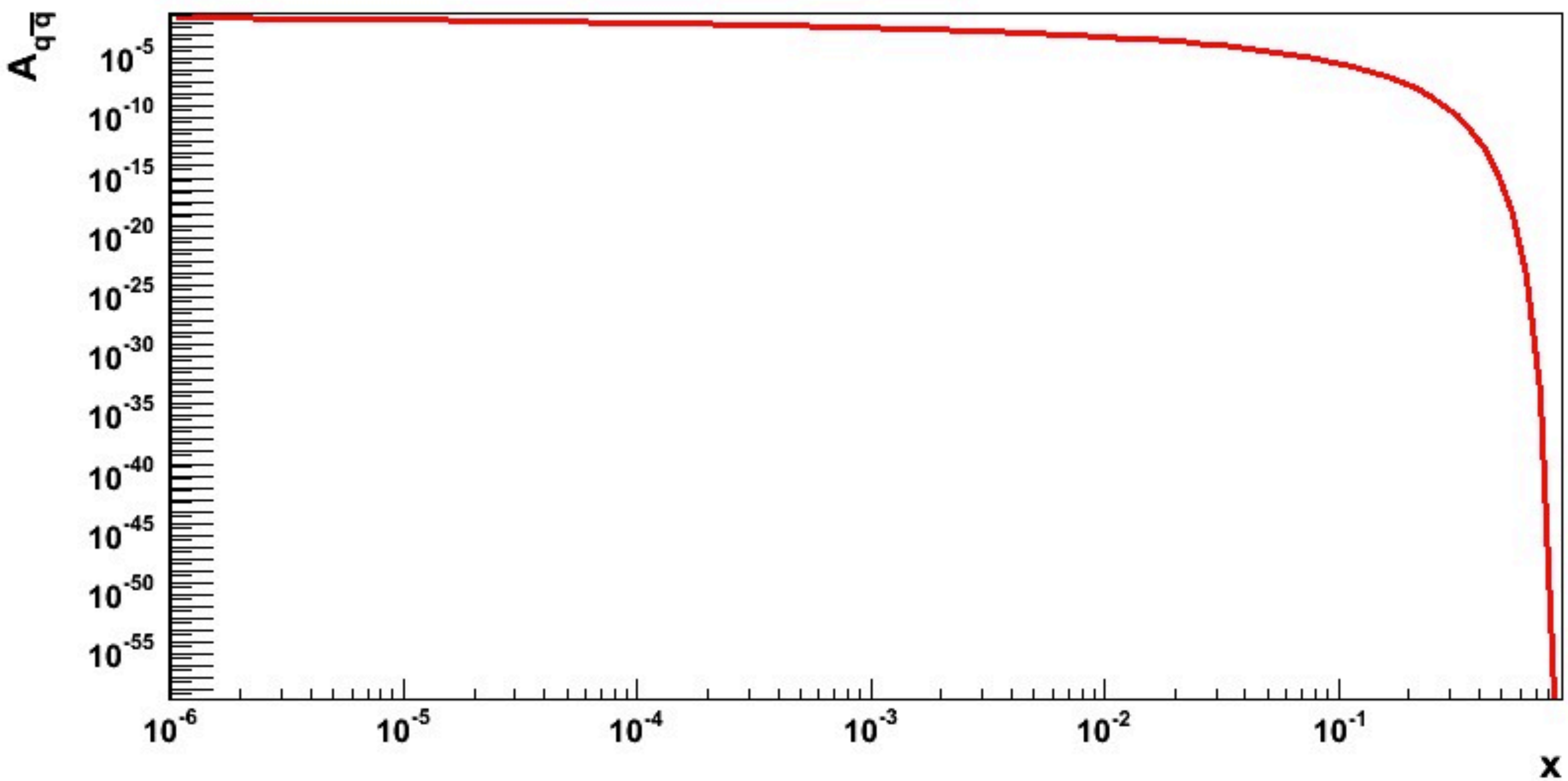
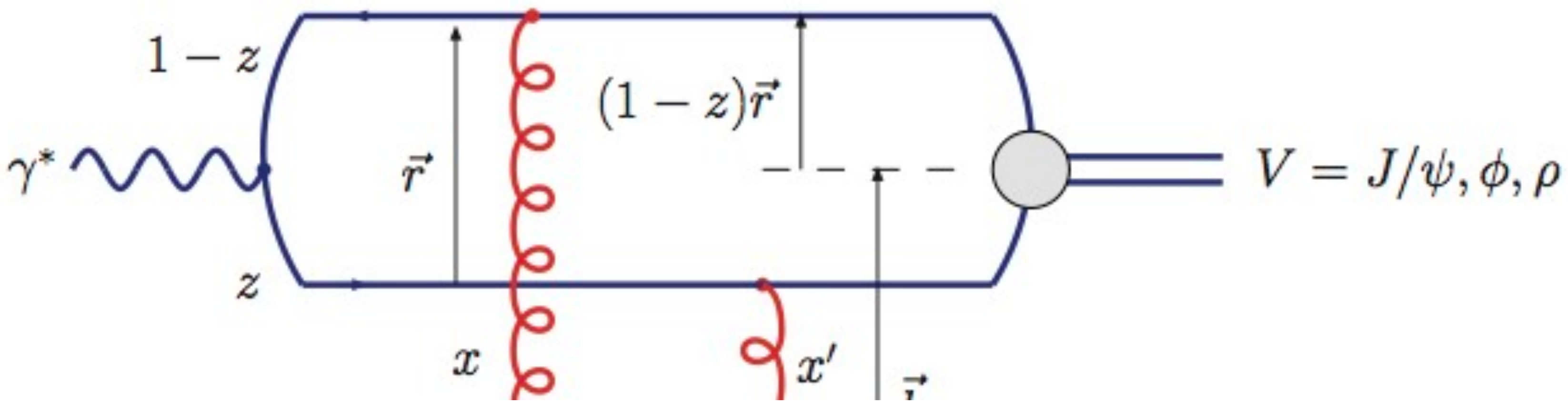


Skewedness Corrections



The two gluons carry different momentum fractions

This is the Skewed effect

In leading ln(1/x) this effect disappears

It can be accounted for by a factor R_g

$$R_g(\lambda) = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + 5/2)}{\Gamma(\lambda + 4)} \qquad \lambda \equiv \frac{\partial \ln \left(\mathcal{A}_{T,L}^{\gamma^* p \to Ep} \right)}{\partial \ln(1/x)}$$

Again, this goes bad for large $x \sim 10^{-2}$!

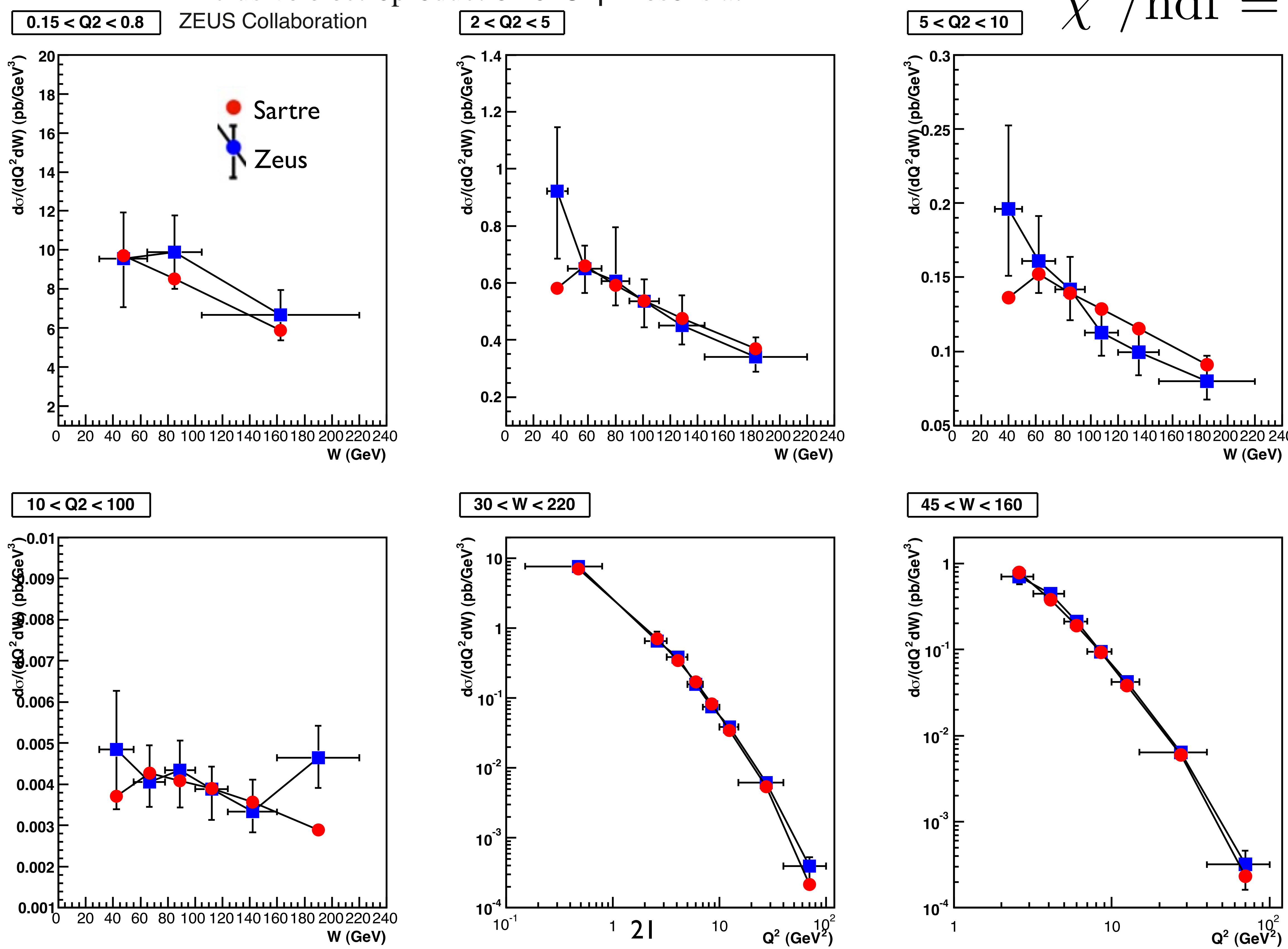
Implemented with exponential damping to control this.

Some *ep* results using tables

Exclusive electroproduction of J/ψ mesons at HERA

ZEUS Collaboration

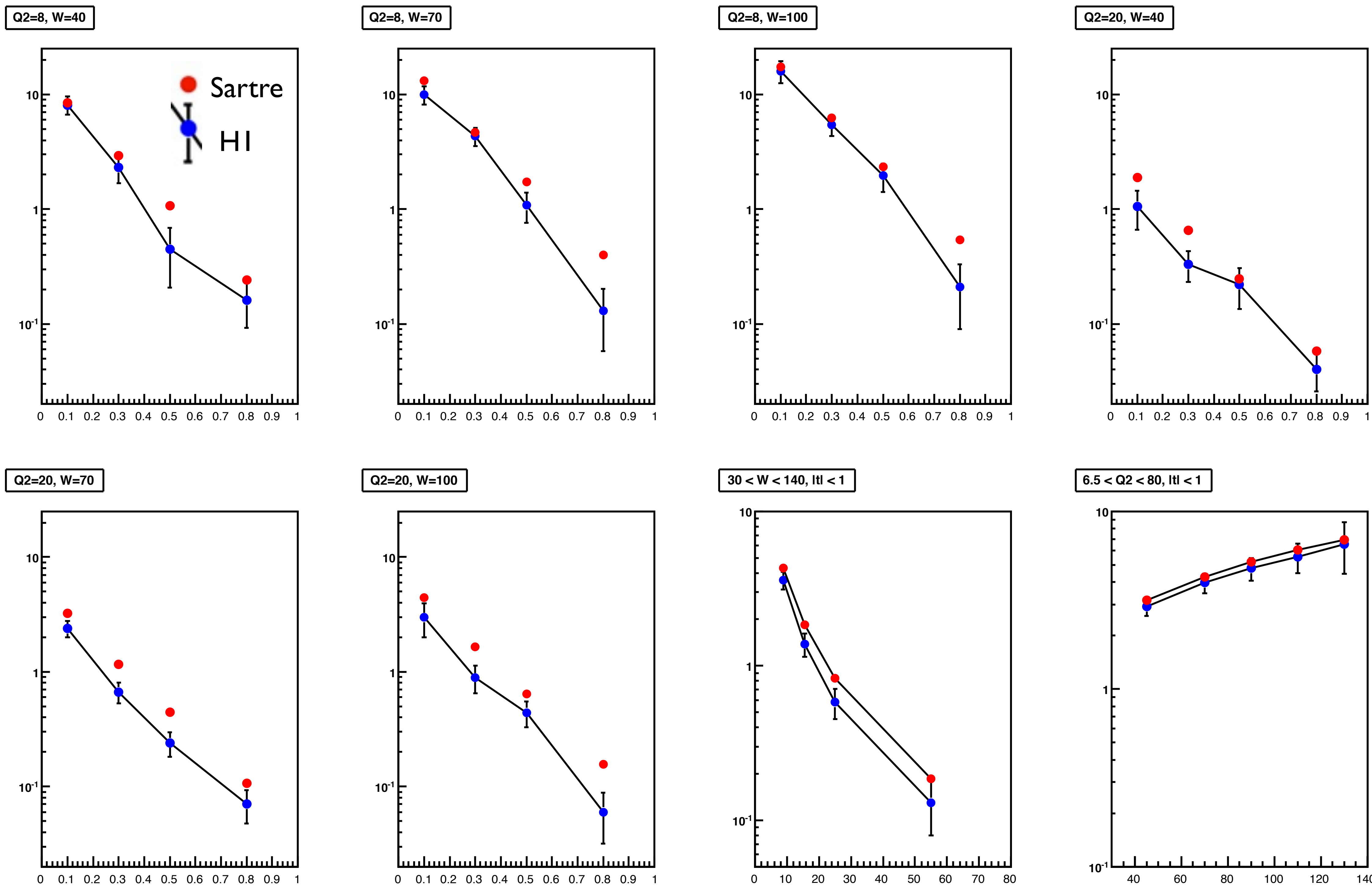
$$\chi^2/\mathrm{ndf} = 0.62$$



Some *ep* results using tables

Measurement of Deeply Virtual Compton Scattering and its t-dependence at HERA
H1 Collaboration

$$\chi^2/\mathrm{ndf} = 5.36$$



$$\chi^2/\mathrm{ndf} = 1.81$$

Going from e$\not p$ to eA

Going from *ep* to eA

ep:

$$\mathrm{Re}(S) = 1 - \mathcal{N}^{(p)}(x, r, \mathbf{b}) = 1 - \frac{1}{2}\frac{\mathrm{d}\sigma^{(p)}_{q\bar{q}}(x, r, \mathbf{b})}{\mathrm{d}^2\mathbf{b}}$$

eA: Independent scattering approximation

$$1 - \mathcal{N}^{(A)} = \prod_{i=1}^{A}\left(1 - \mathcal{N}^{(p)}(x, r, |\mathbf{b} - \mathbf{b}_i|)\right)$$

Assume the Woods-Saxon distribution

bSat:

$$\frac{\mathrm{d}\sigma^{A}_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}r^2\alpha_s(\mu^2)xg(x, \mu^2)\sum_{i=1}^{A}T_p(\mathbf{b} - \mathbf{b}_i)\right)\right]$$

Generating a Nucleus

Generate radii according to the Woods-Saxon distribution

$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{r - R_0}{d}}} \qquad \rho(r) = \frac{\mathrm{d}^3 N}{\mathrm{d}^3 \mathbf{r}}$$

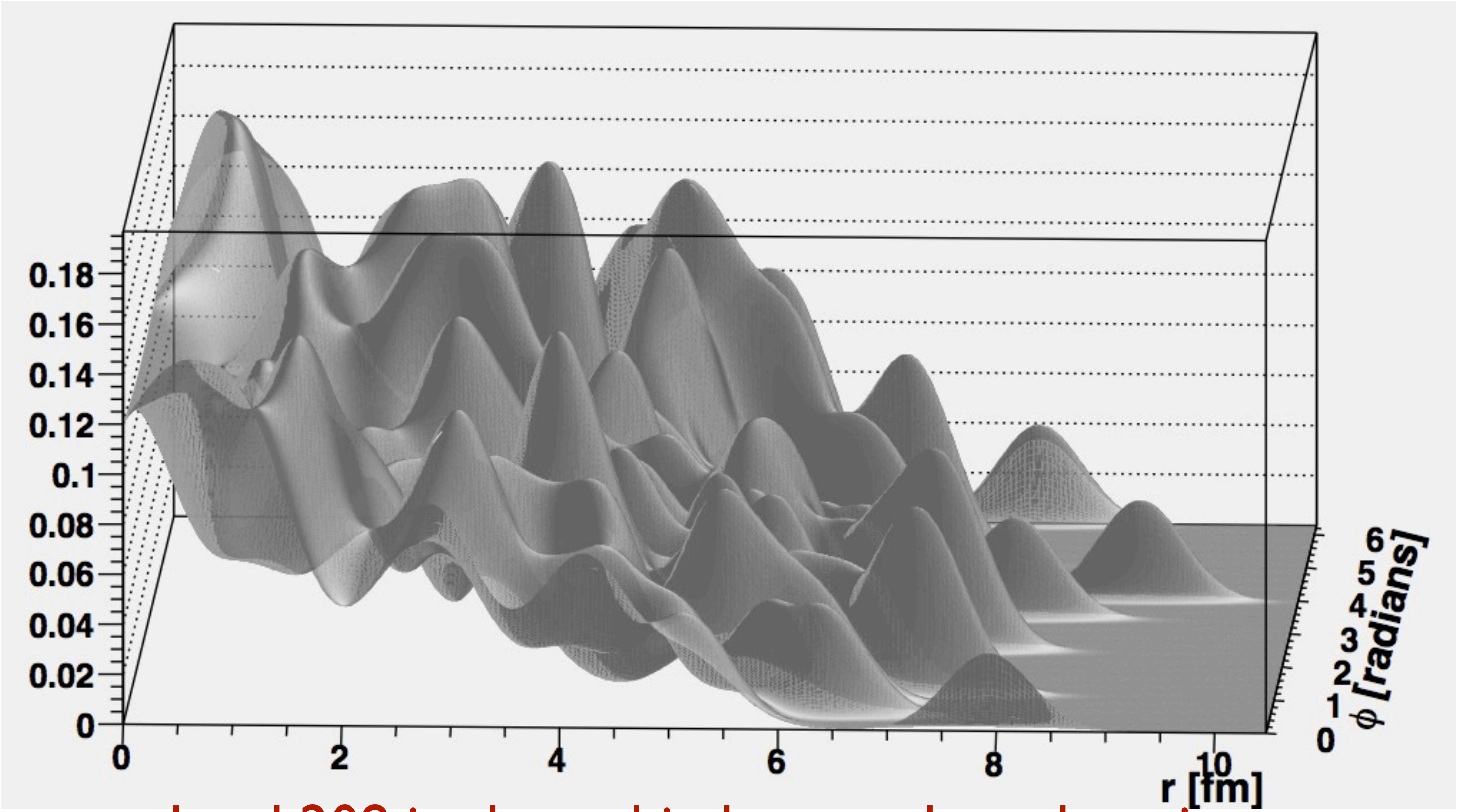
First generate according to r: $\dfrac{\mathrm{d}N}{\mathrm{d}r} = 4\pi r^2 \rho(r)$

Then generate angular distributions uniform in ϕ and $\cos(\theta)$

This is done with a condition that two nucleons can not be within a core distance of ~0.8fm.

If they are: regenerate angles (not radius!)

Generating a Nucleus



Lead 208 in the r-phi plane, each nucleon is supplemented with a Gaussan width (bSat).

Going from *ep* to eA

Another difference in eA:
The Nucleus can break up
into colour neutral fragments!

When the nucleus breaks up, the scattering is called
incoherent

When the nucleus stays intact, the scattering is called
coherent

Total cross-section = incoherent + coherent

Incoherent Scattering

Nucleus dissociates ($f \neq i$):

Good, Walker

$$\sigma_{\mathrm{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle$$

$$= \sum_{f} \langle i|\mathcal{A}\overbrace{|f\rangle^{\dagger} \langle f|}^{\text{complete set}}\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

$$= \left\langle i \left| |\mathcal{A}|^2 \right| i \right\rangle - \left|\langle i|\mathcal{A}|i\rangle\right|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - \left|\langle \mathcal{A} \rangle\right|^2$$

The incoherent CS is the variance of the amplitude!!

$$\frac{\mathrm{d}\sigma_{\mathrm{total}}}{\mathrm{d}t} = \frac{1}{16\pi} \left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi} \left|\langle \mathcal{A} \rangle\right|^2$$

Defining the average

$$\frac{\mathrm{d}\sigma_{\mathrm{total}}}{\mathrm{d}t} = \frac{1}{16\pi}\left\langle |\mathcal{A}|^2 \right\rangle_\Omega \qquad \frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle \mathcal{A}\rangle_\Omega\right|^2$$

Define average: $$\langle \mathcal{O}\rangle_\Omega \approx \frac{1}{C_{\mathrm{max}}}\sum_{j=1}^{C_{\mathrm{max}}} \mathcal{O}(\Omega_j)$$

$$\mathcal{A}(\Omega_j) = \int \mathrm{d}r\frac{\mathrm{d}z}{4\pi}\mathrm{d}^2\mathbf{b}(\Psi_V^*\Psi)(r,z)2\pi r b J_0([1-z]r\Delta)e^{-i\mathbf{b}\cdot\boldsymbol{\Delta}}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}(x,r,\mathbf{b},\Omega_j)$$

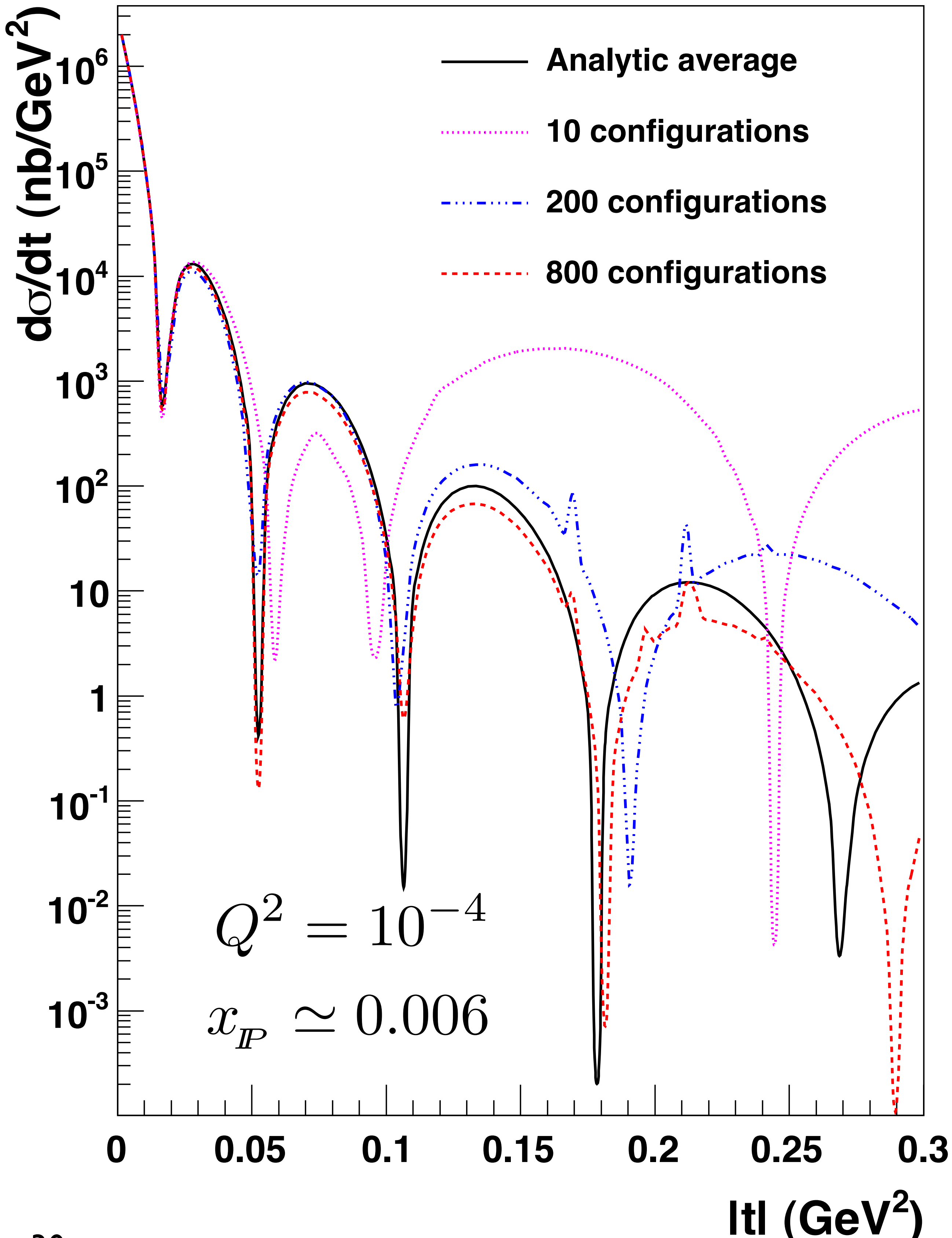
4 four-dimensional integrations for each phase-space point and configuration

Re, Im, L, T

How many configurations???

Convergence of sum:

Need ~1000 configurations to describe 5th minimum!!



Convergence of sum:

Problem with convergence of distribution at large |t|:

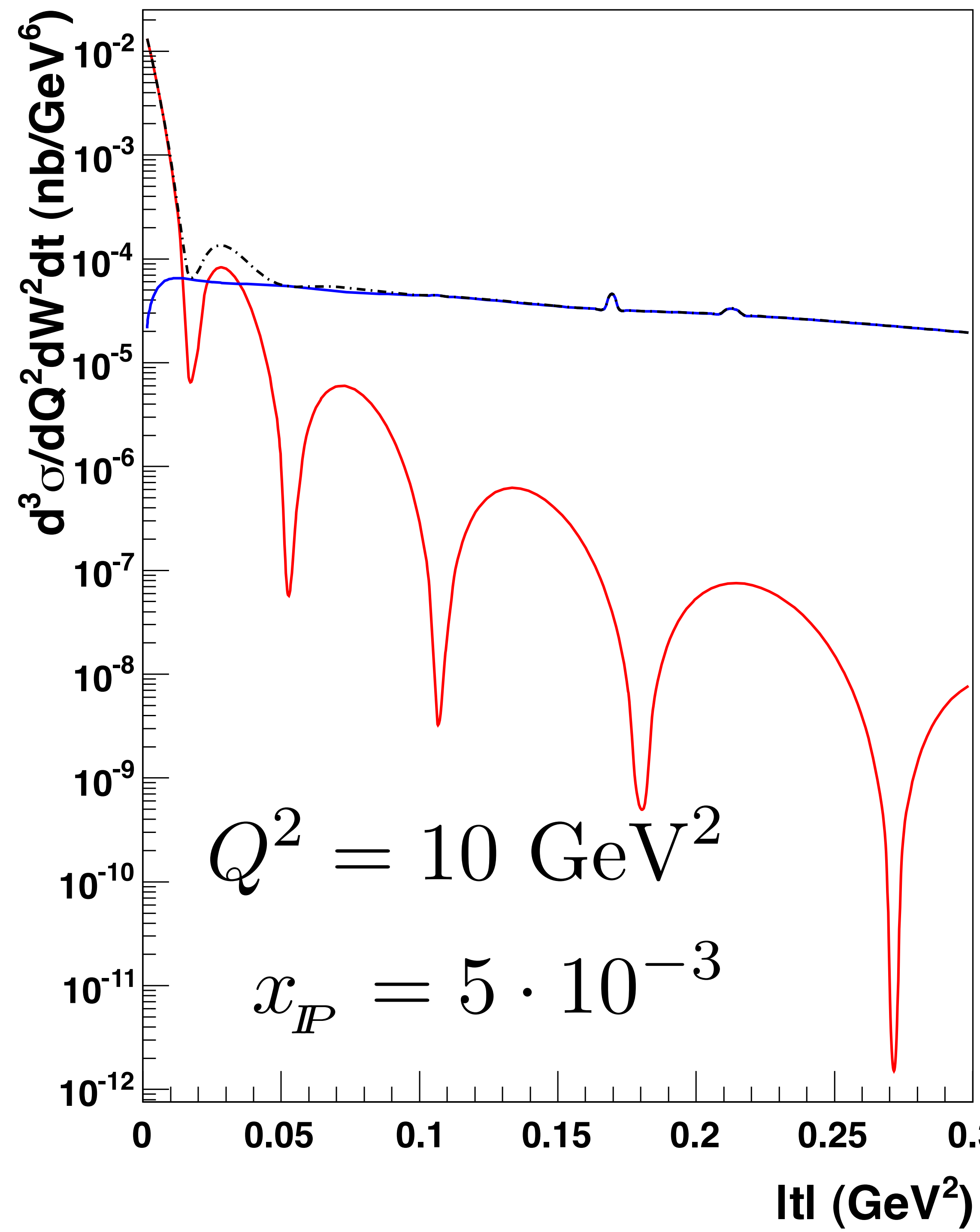
Average (coherent)

<<<<<

Variance (incoherent)

Or: At large |t| the nucleus is probed at a smaller scale.

$\Delta = \sqrt{-t}$ is the Fourier conjugate of *b*.



Convergence of sum:

Problem with convergence of distribution at large |t|:

Average (coherent)

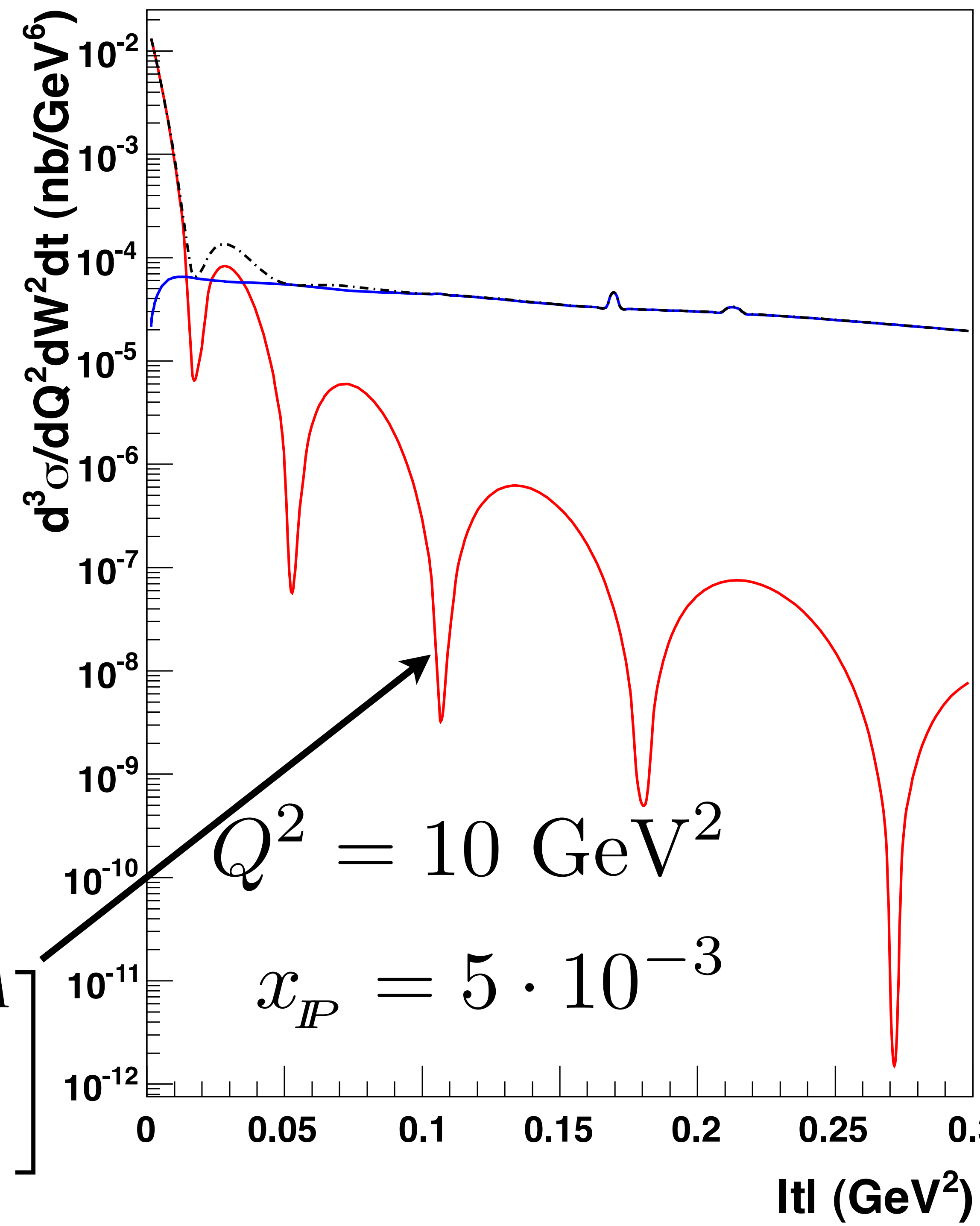
<<<<<

Variance (incoherent)

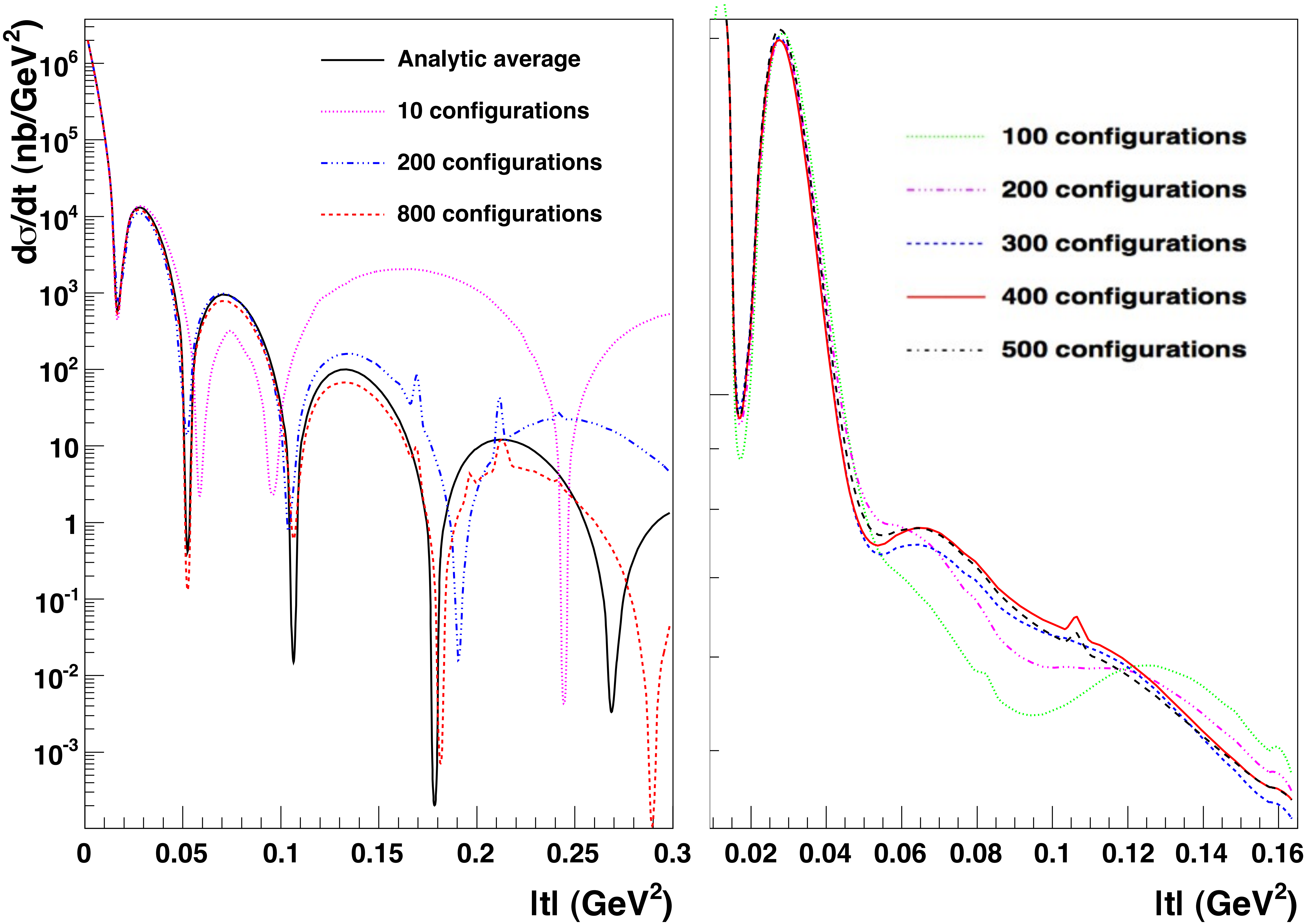
Solution

Calculate the average from:

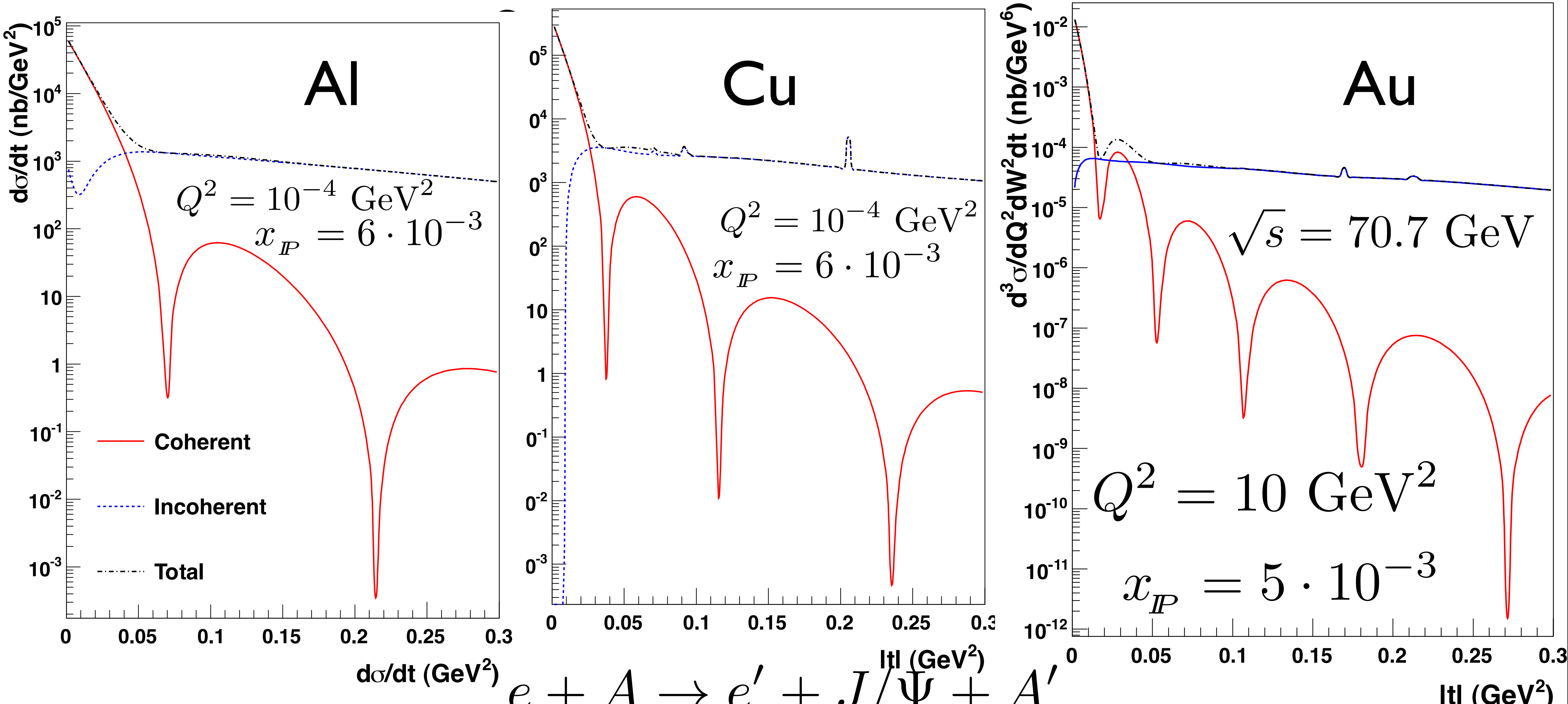
$$\left\langle \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} \right\rangle_\Omega = 2\left[1-\left(1-\frac{T_A(\mathbf{b})}{2}\sigma_{q\bar{q}}^{(p)}\right)^A\right]$$



An Impact parameter dipole saturation model - Kowalski, Henri & Derek Teaney Phys.Rev. D68 (2003) 114005 . hep-ph/0304189


dσ/dt (nb/GeV²)
Analytic average
10 configurations
200 configurations
800 configurations
100 configurations
200 configurations
300 configurations
400 configurations
500 configurations
|t| (GeV²)
|t| (GeV²)

Some eA results w/o tables



$$e + A \to e' + J/\Psi + A'$$

Note: the b-distribution one gets by Fourier transform of the coherent t-distribution.

The incoherent distribution contains all nucleon correlations in the nucleus - very interesting in itself!!

Generating events

How Sartre works

4 four-dimensional integrations for each phase-space point and configuration

~1600 4D integrals/point

Use 3D lookup tables in Q^2, W^2, t independent of s and use the Open Science Grid to produce the tables.

Four tables to create a cross-section point:

$$\langle\, |\mathcal{A}_T|^2 \,\rangle, |\langle \mathcal{A}_T \rangle|\,, \langle\, |\mathcal{A}_L|^2 \,\rangle, |\langle \mathcal{A}_L \rangle|$$

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}Q^2\mathrm{d}W^2\mathrm{d}t} = f_T^\gamma \langle\, |A_T|^2 \,\rangle + f_L^\gamma \langle\, |A_L|^2 \,\rangle$$

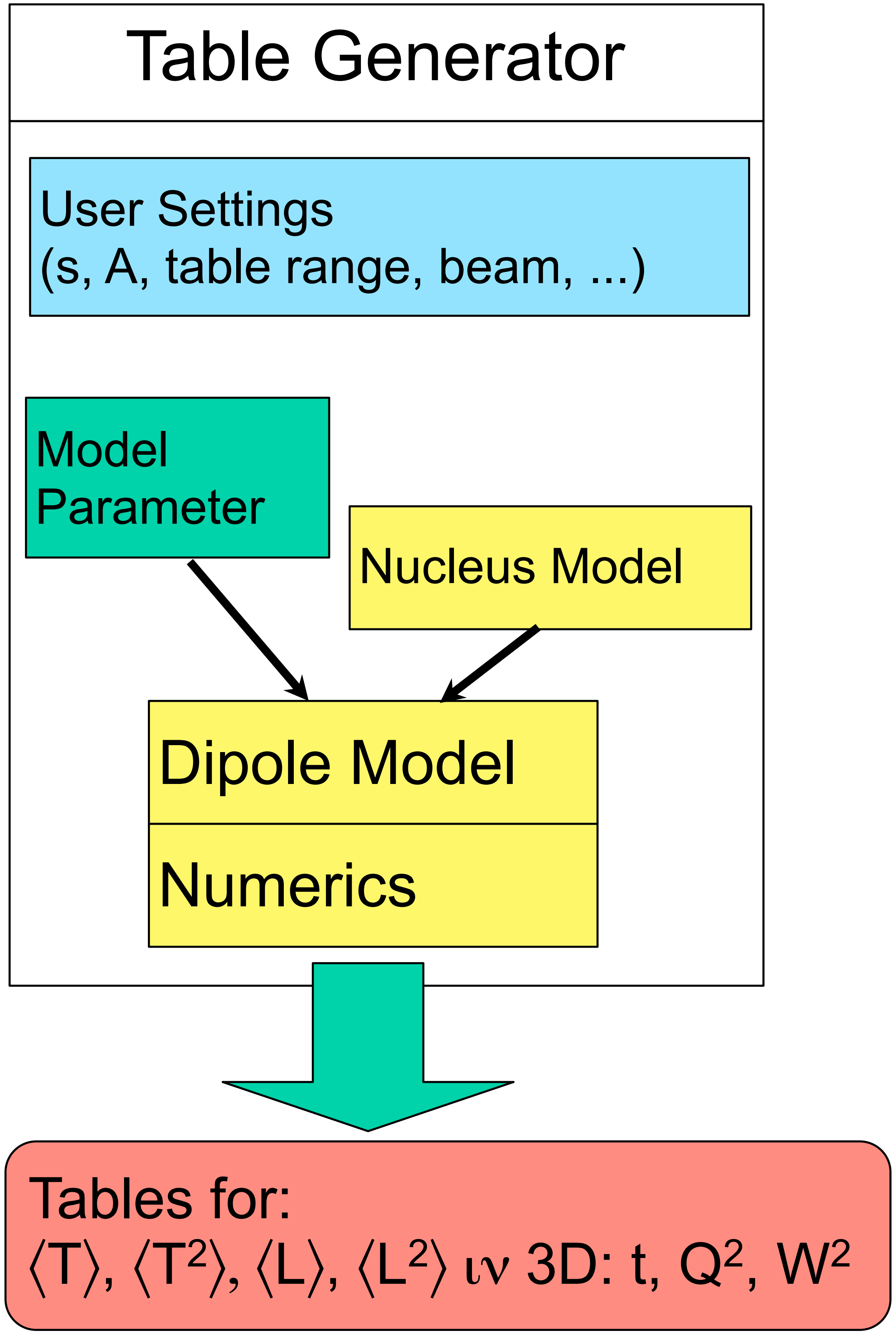
Transverse if:

$$\frac{f_T^\gamma \langle\, |\mathcal{A}_T| \,\rangle}{f_T^\gamma \langle\, |\mathcal{A}_T| \,\rangle + f_L^\gamma \langle\, |\mathcal{A}_L| \,\rangle} > R$$

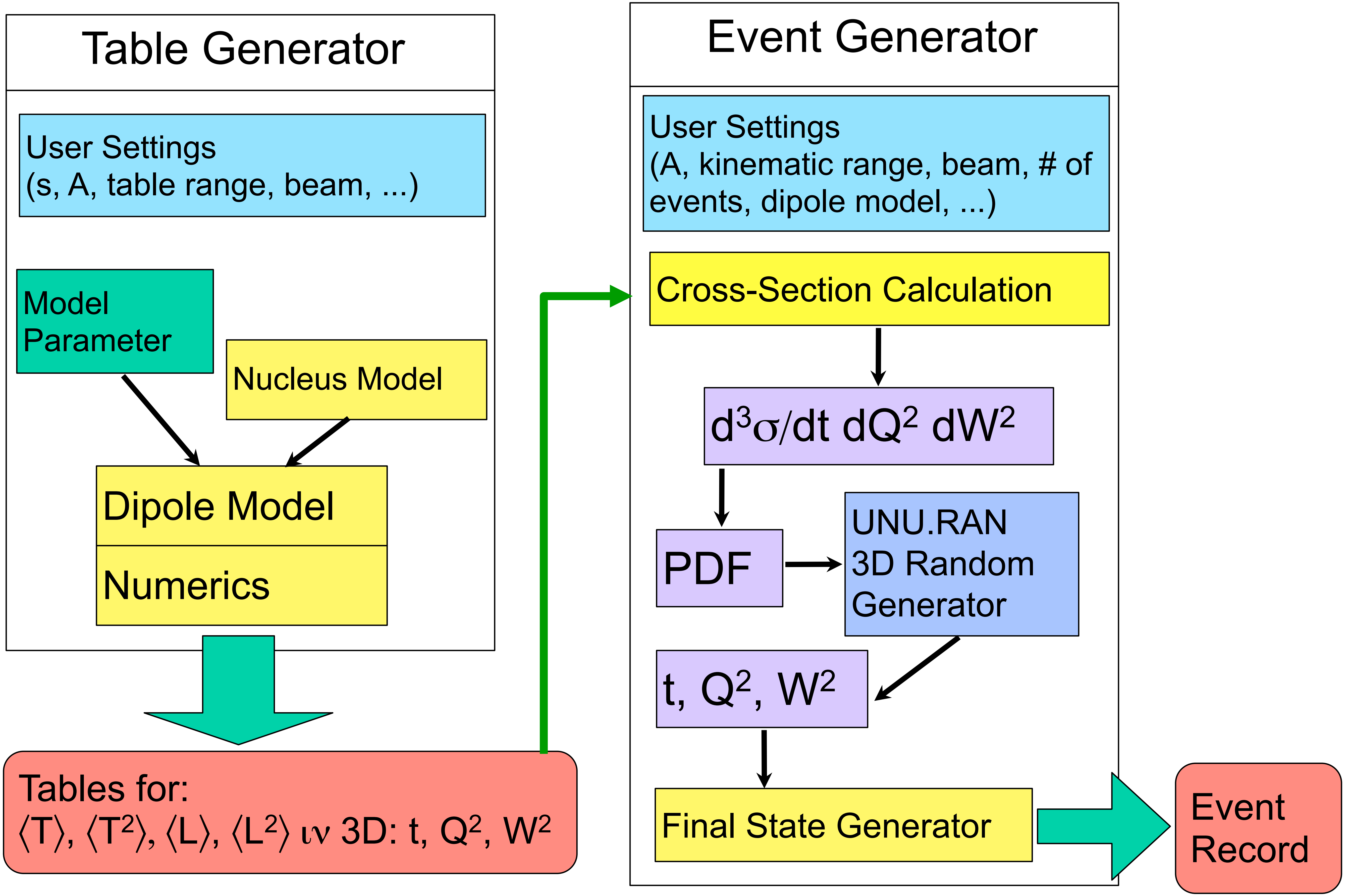
Breakup if:

$$\frac{|\langle A_T \rangle|^2 - \langle\, |A_T|^2 \,\rangle}{|\langle A_T \rangle|^2} > R$$

How Sartre works



How Sartre works



Slide from T. Ullrich

Detecting Nuclear Breakup

- Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible
- Focus on n emission
  - Zero-Degree Calorimeter
  - Requires careful design of IR
- Additional measurements:
  - Fragments via Roman Pots
  - γ via EMC

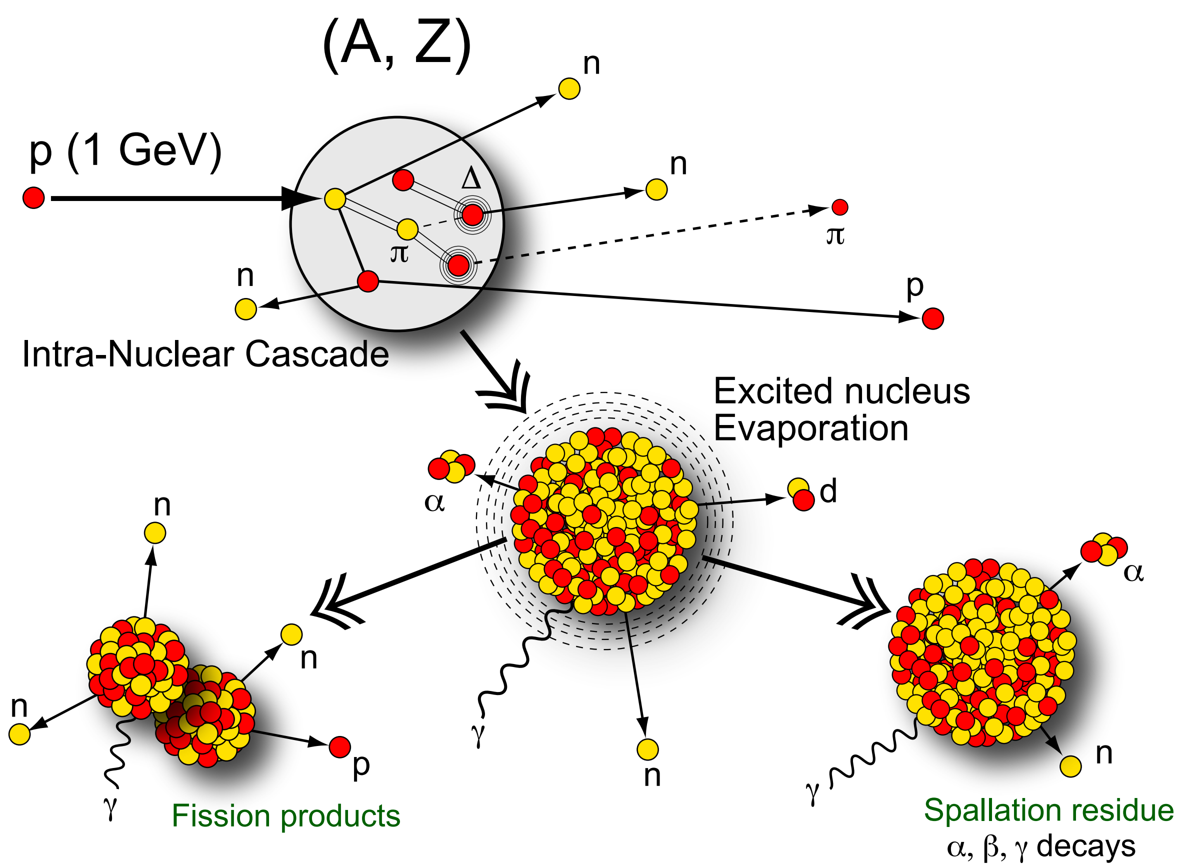
Traditional modeling done in pA:

Intra-Nuclear Cascade

- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

De-Excitation

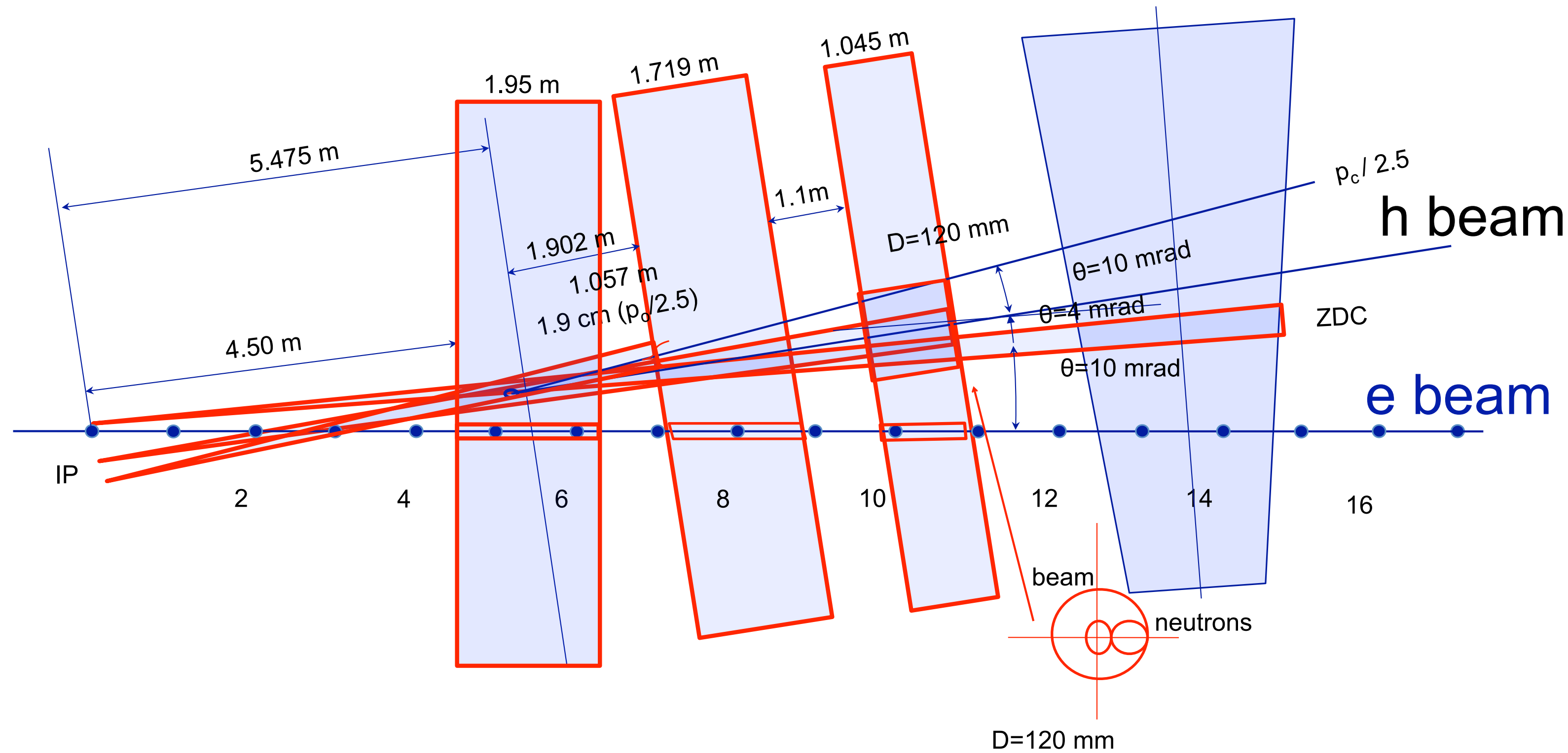
- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)



Experimental Reality

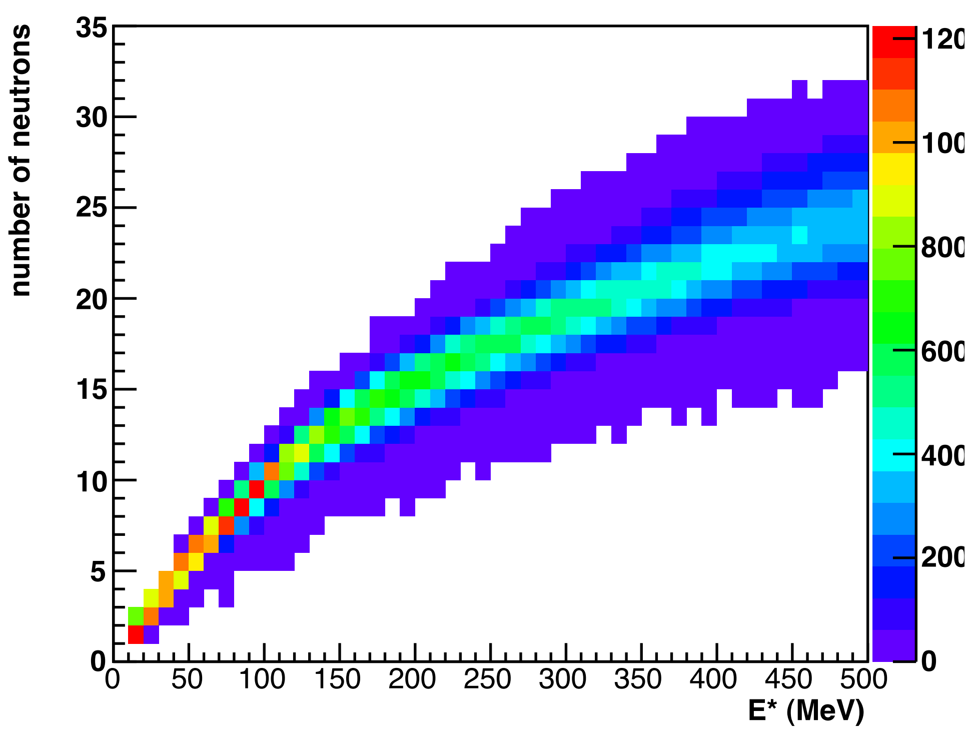
Here eRHIC IR layout:

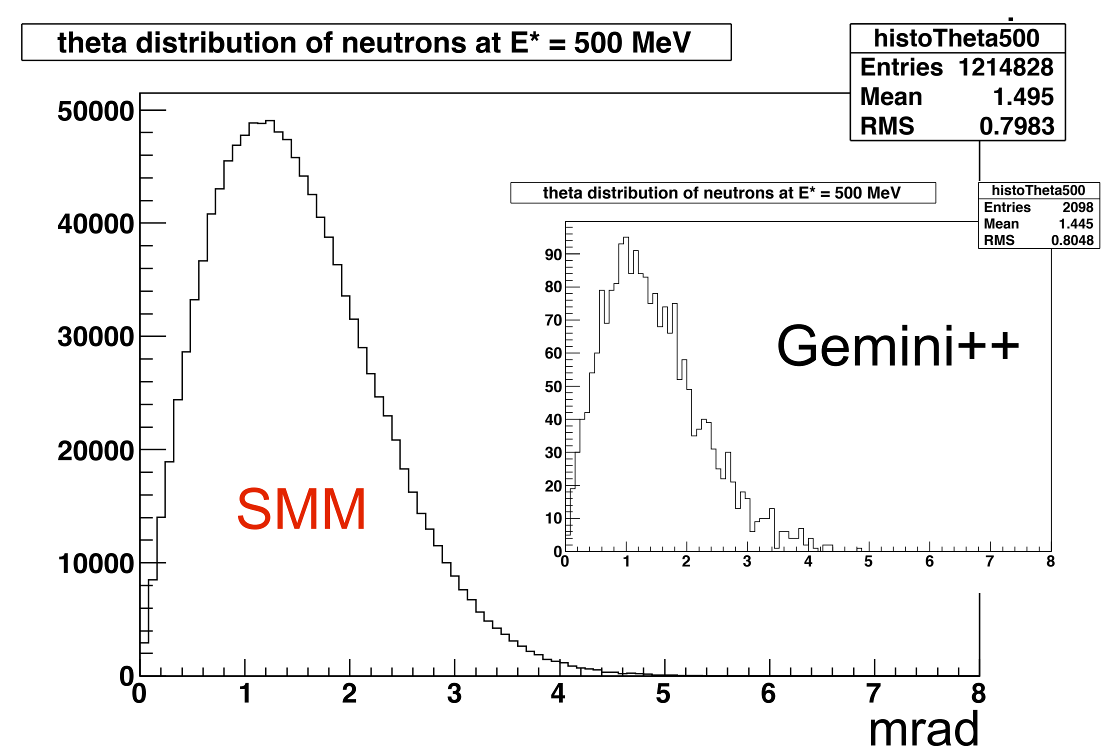
Need ±X mrad opening through triplet for *n* and room for ZDC



Big questions:

- Excitation energy E*?
- ep: $d\sigma/M_Y \sim 1/M_Y^2$
- eA? Assume ep and use $E^* = M_Y - m_p$ as lower limit





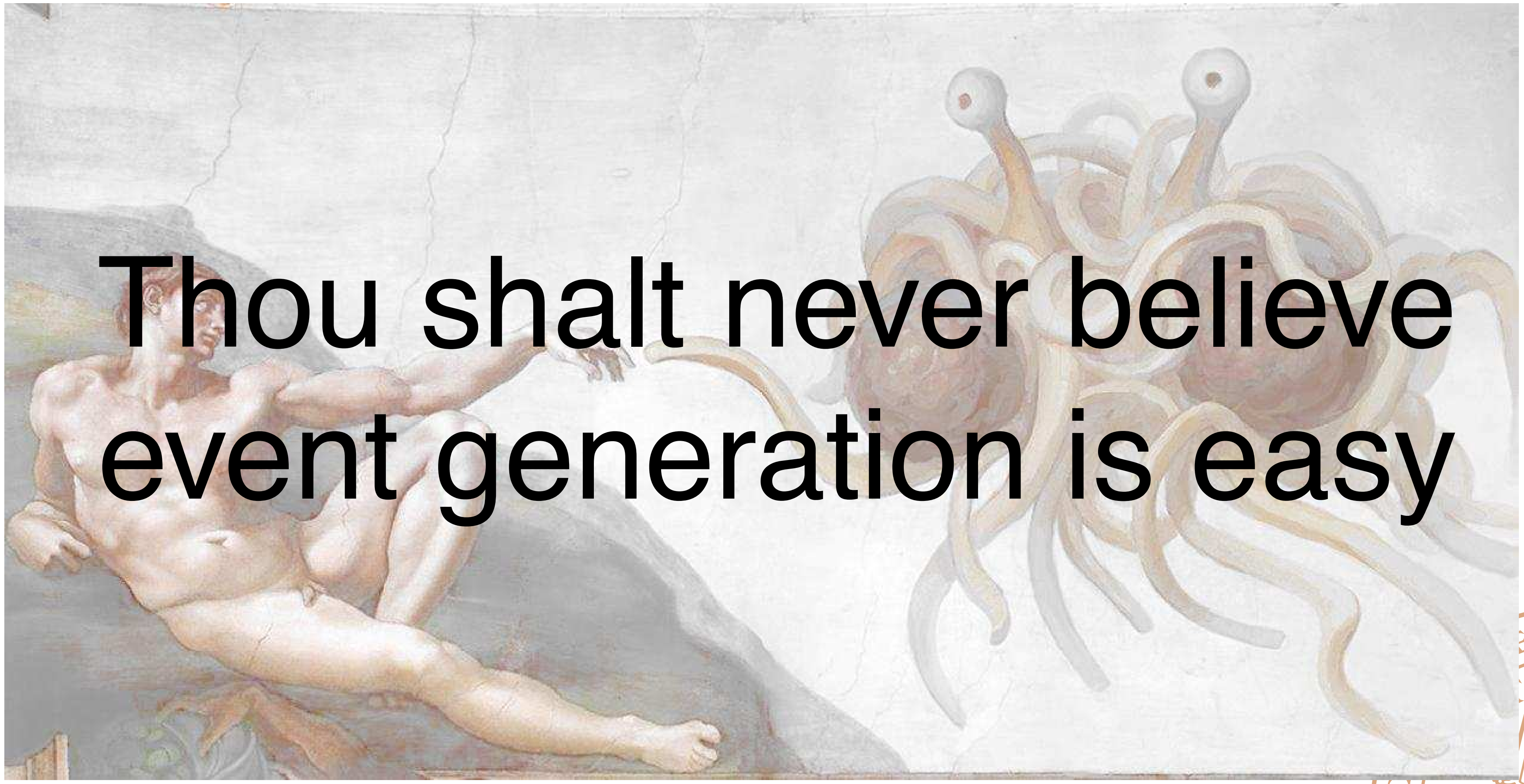
Final notes:

When presented like this, things seem quite straight forward and simple,

BUT, don't forget:

Final notes:

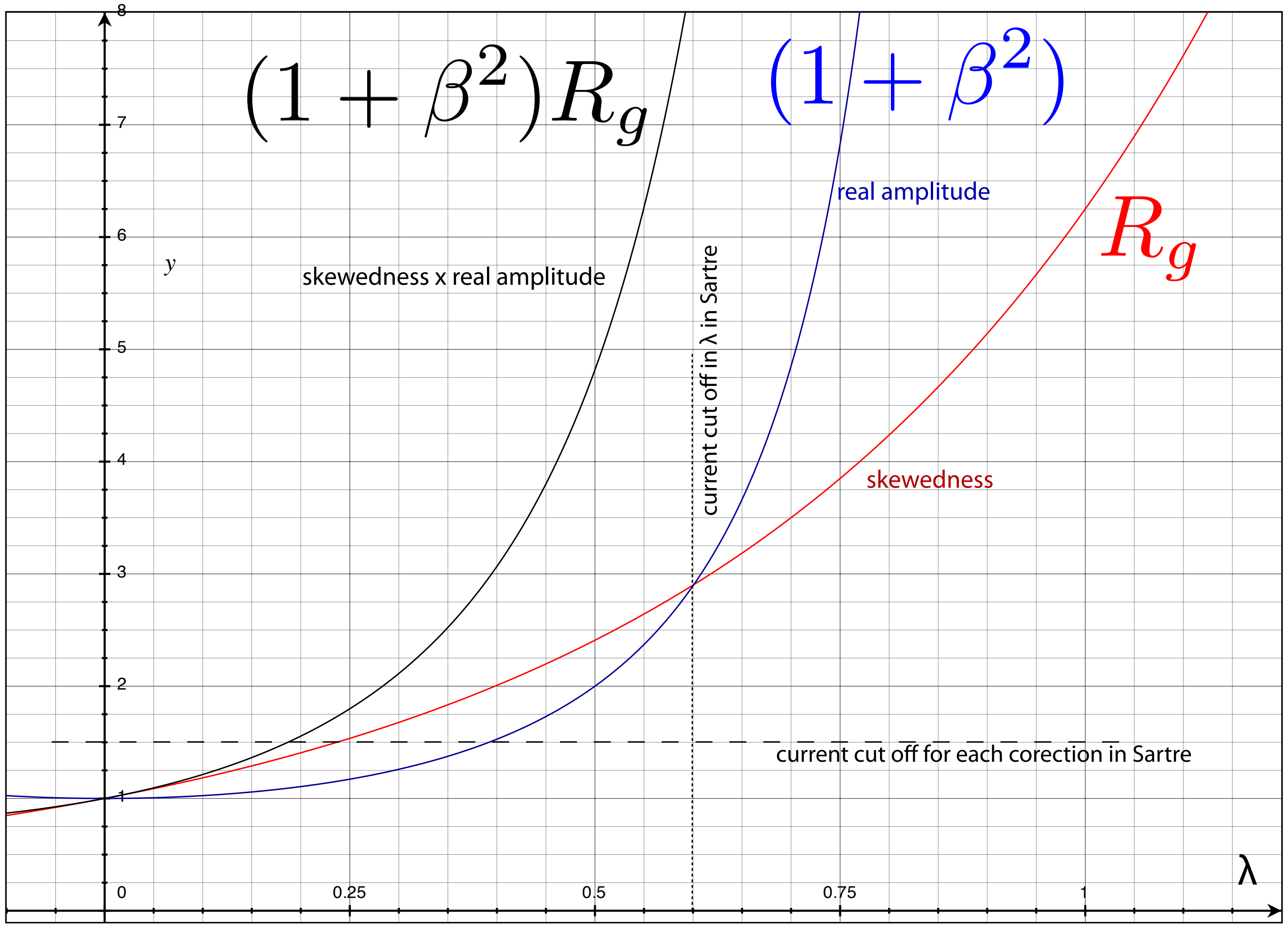
The First Commandment of Event Generation



Final notes:

We’ve had (and still have) a plethora of technical and numerical problems:

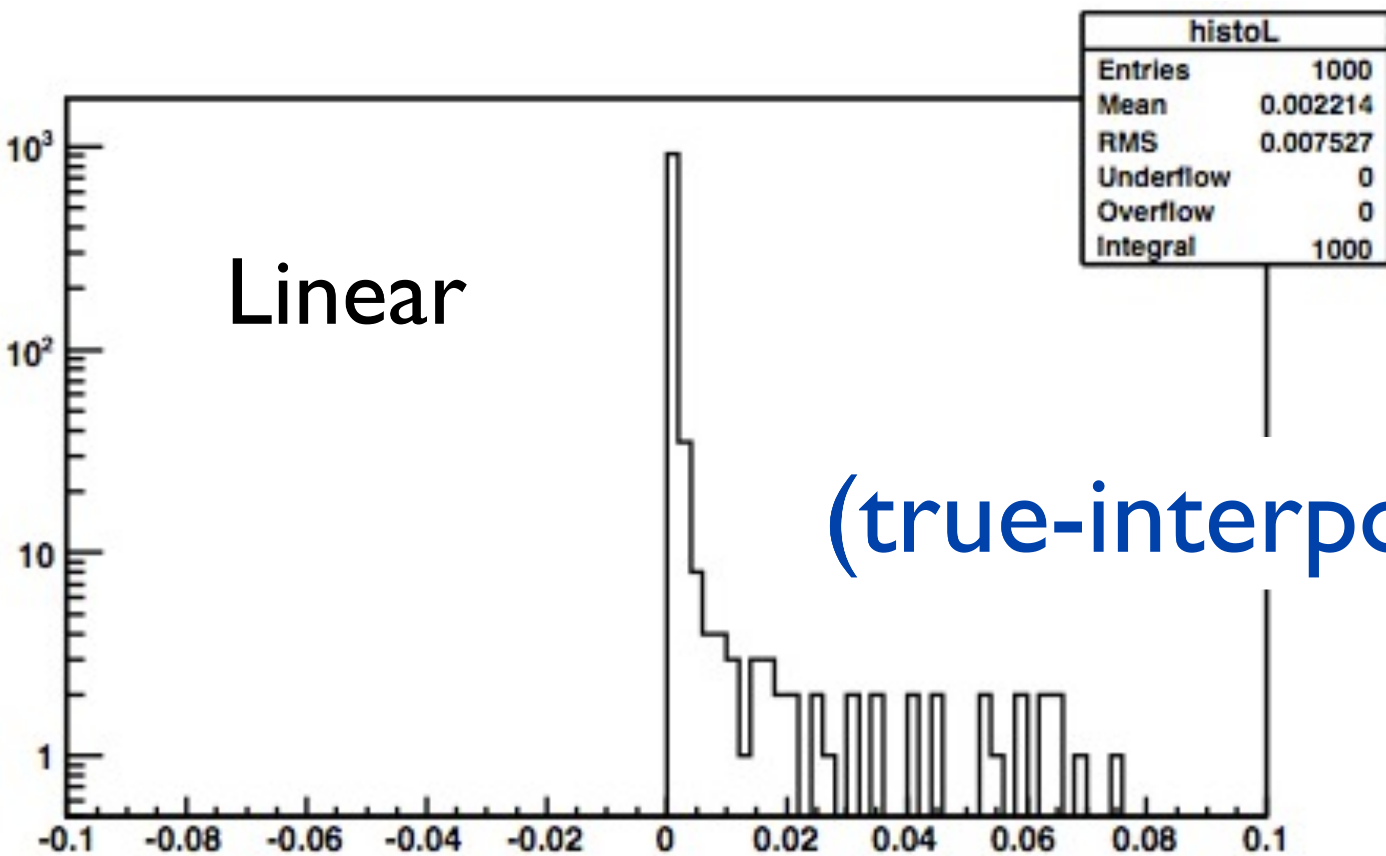
Real and skewedness corrections can be tweaked to better describe the cross-sections

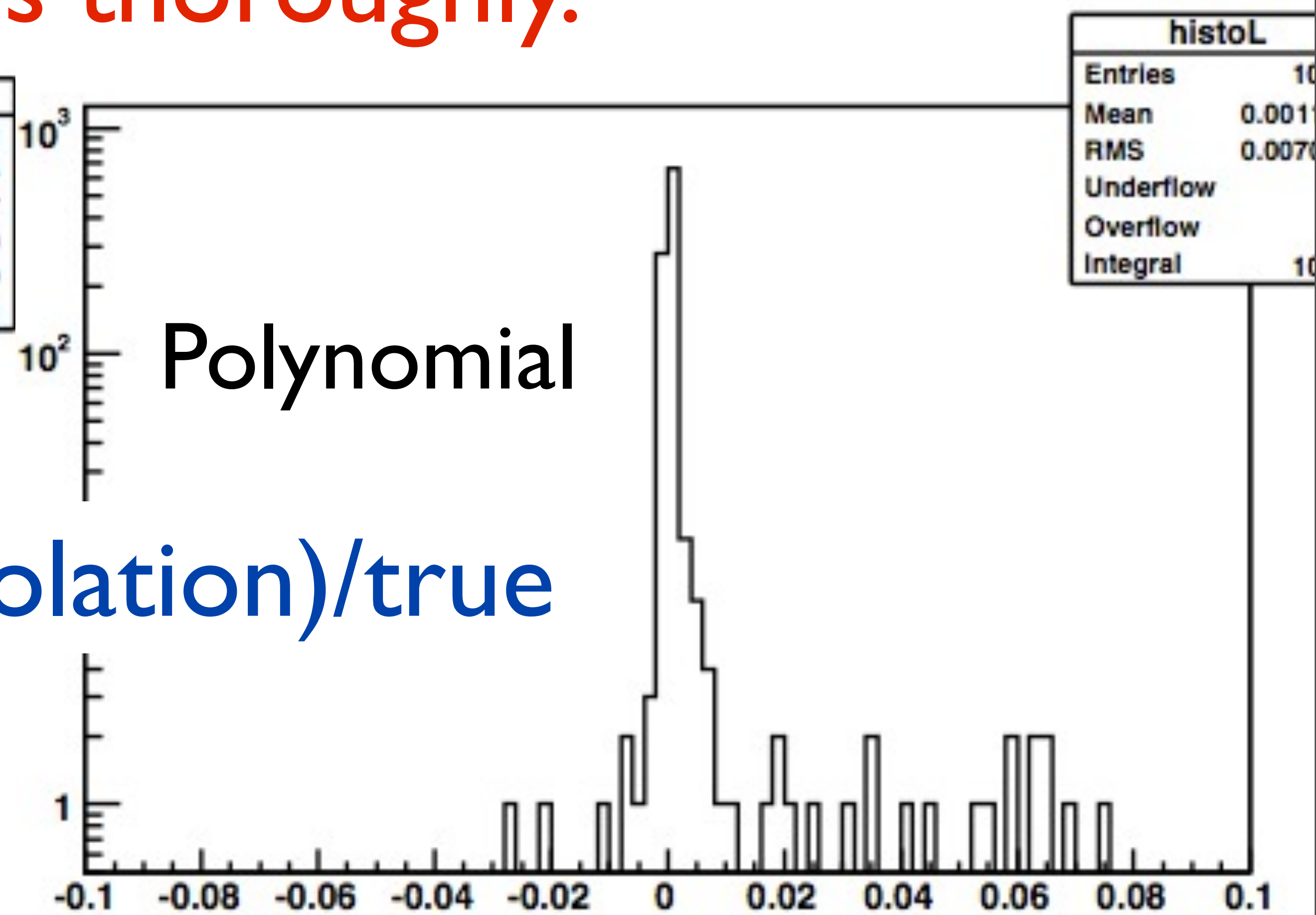


Final notes:

We’ve had (and still have) a plethora of technical and numerical problems:

Linear interpolation -> a bias to small values, switched to a polynomial interpolation, need to adjust the parameters thoroughly.



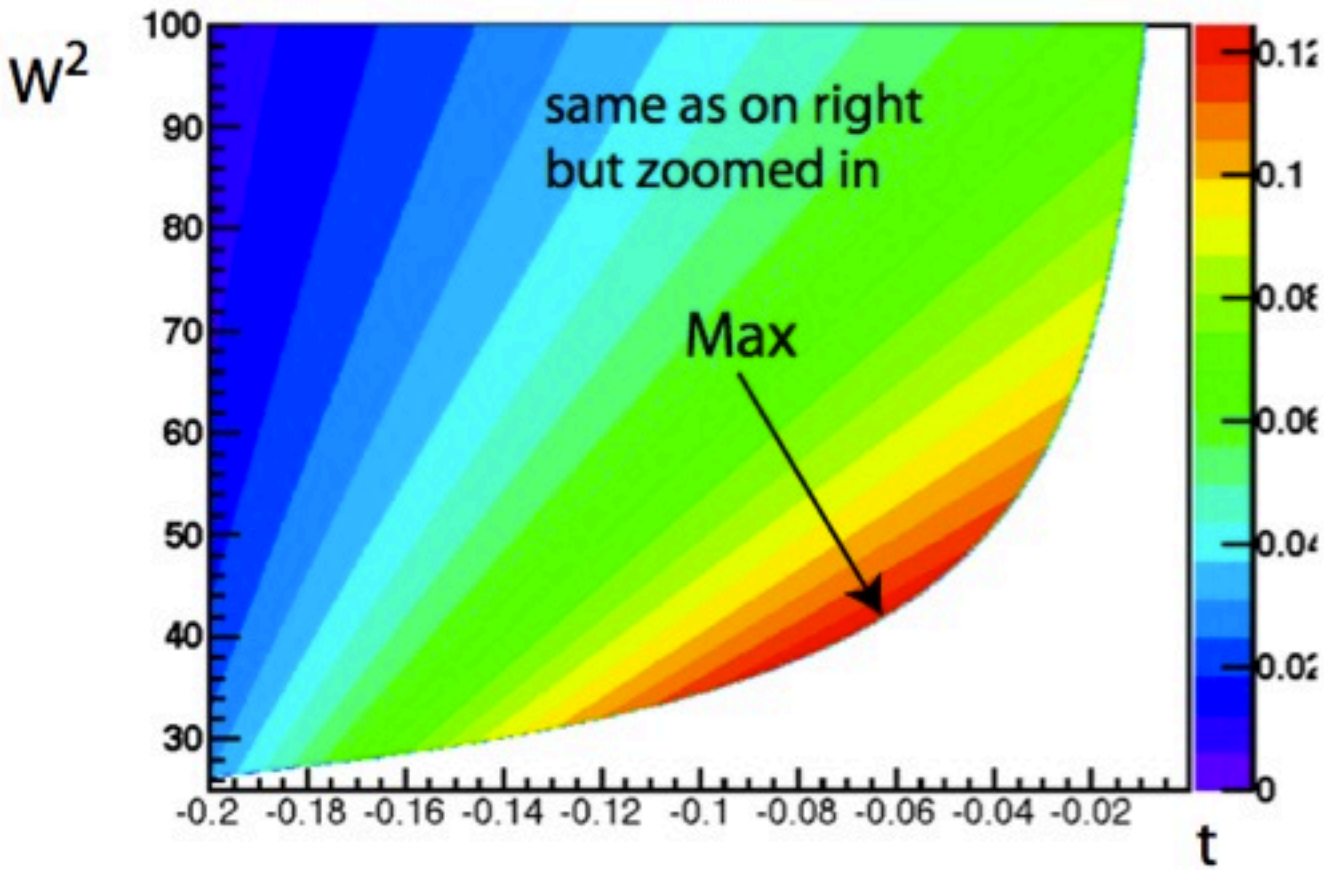


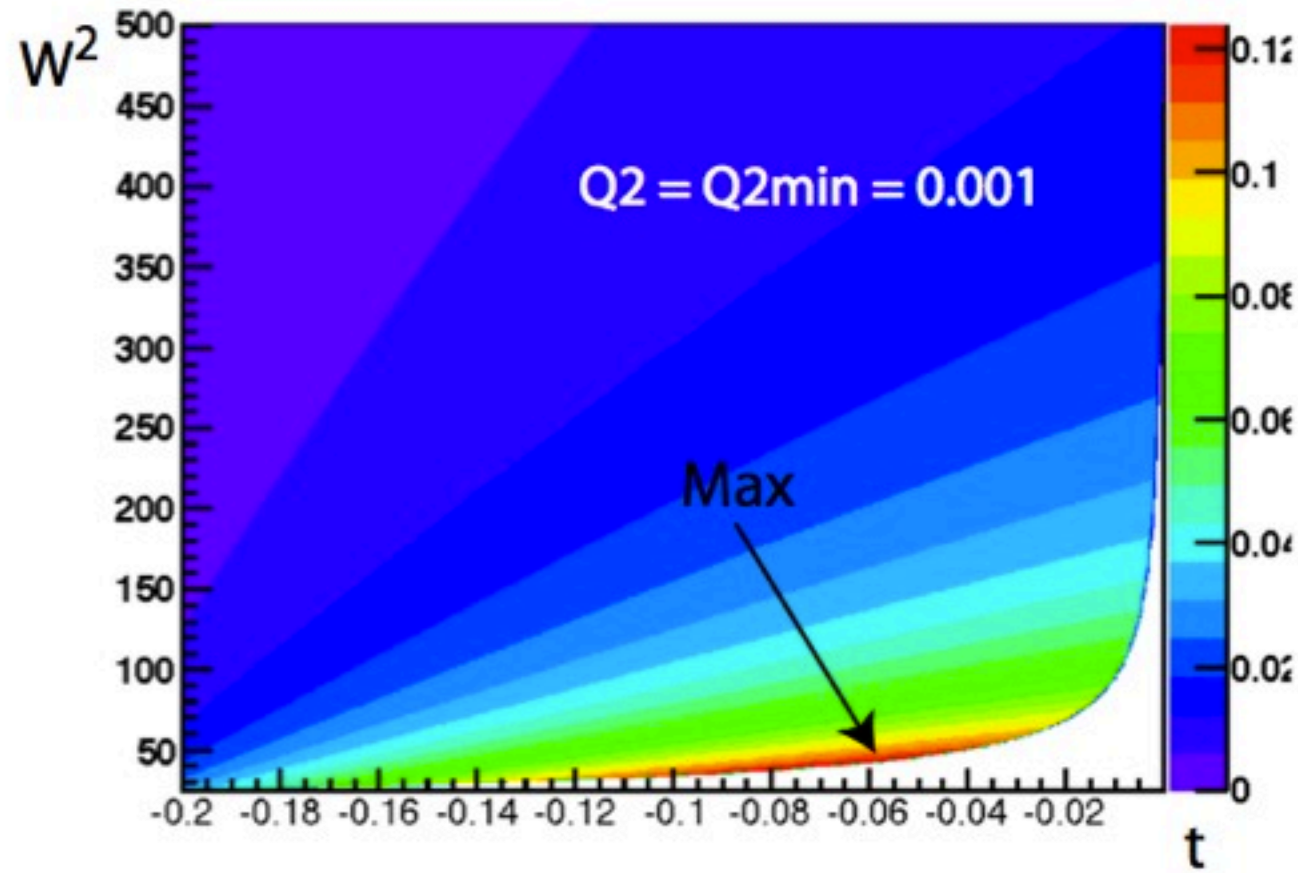
(true-interpolation)/true

Final notes:

We've had (and still have) a plethora of technical and numerical problems:

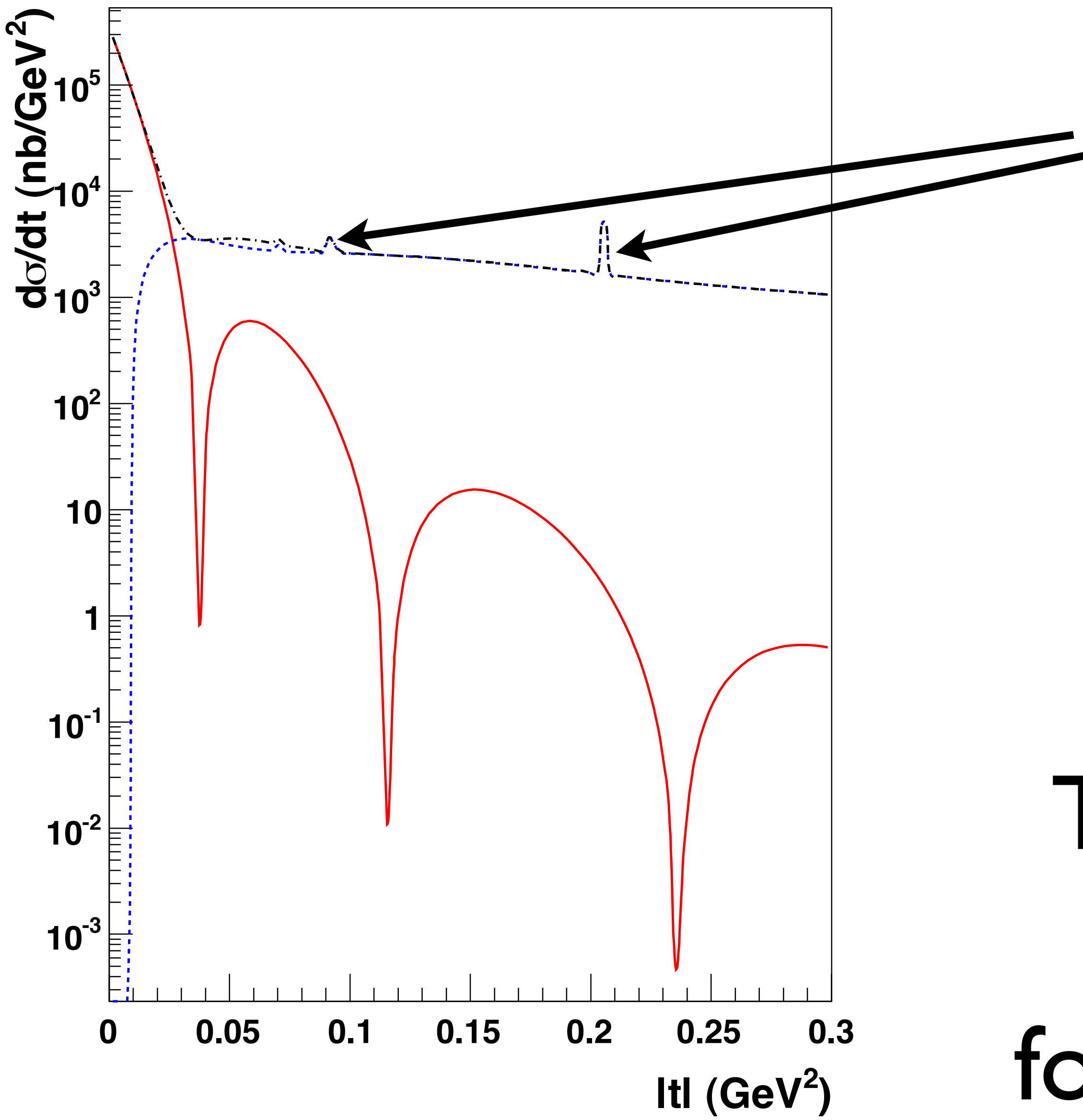
Using UNU.RAN to generate events from the distribution. This has to be set-up with the maximum value in the distribution. It's been a lot of cooking and trial and error to find a reliable method for this.





Final notes:

We've had (and still have) a plethora of technical and numerical problems:



Spikes in the distribution!!

Each phase-space point is the result of 1600 4d integrals.

In a few % of the points, there is a spike.

This will ruin the MC-generation, unless controlled!

These spikes comes from only a few integrals. I may have just found a way to identify the rotten eggs and exclude them.

Summary and outlook

We have developed a method to calculate exclusive diffractive vector meson production and DVCS in eA collisions.

We are currently implementing it in a Monte Carlo event generator called Sartre.

So far it has only been tested for *ep*, and describes the data well.

Sartre can also be extended to the general diffractive process:

$$e + A \to e' + X + A'$$

Summary and outlook

We have developed a method to calculate exclusive diffractive vector meson production and DVCS in eA collisions.

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Sartre can also be extended to the general diffractive process:

$$e + A \rightarrow e' + X + A'$$

Thank you!

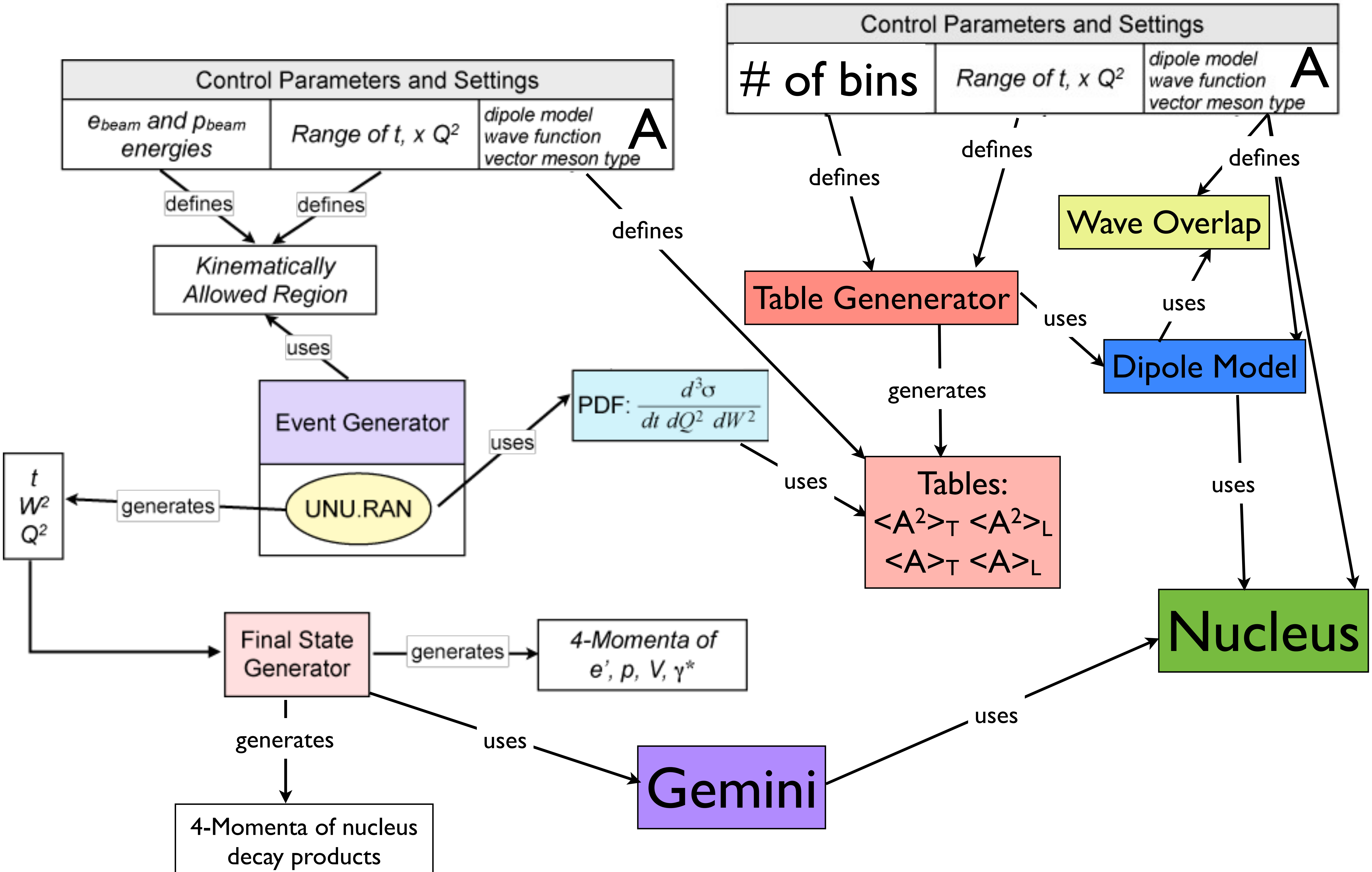
BACKUP

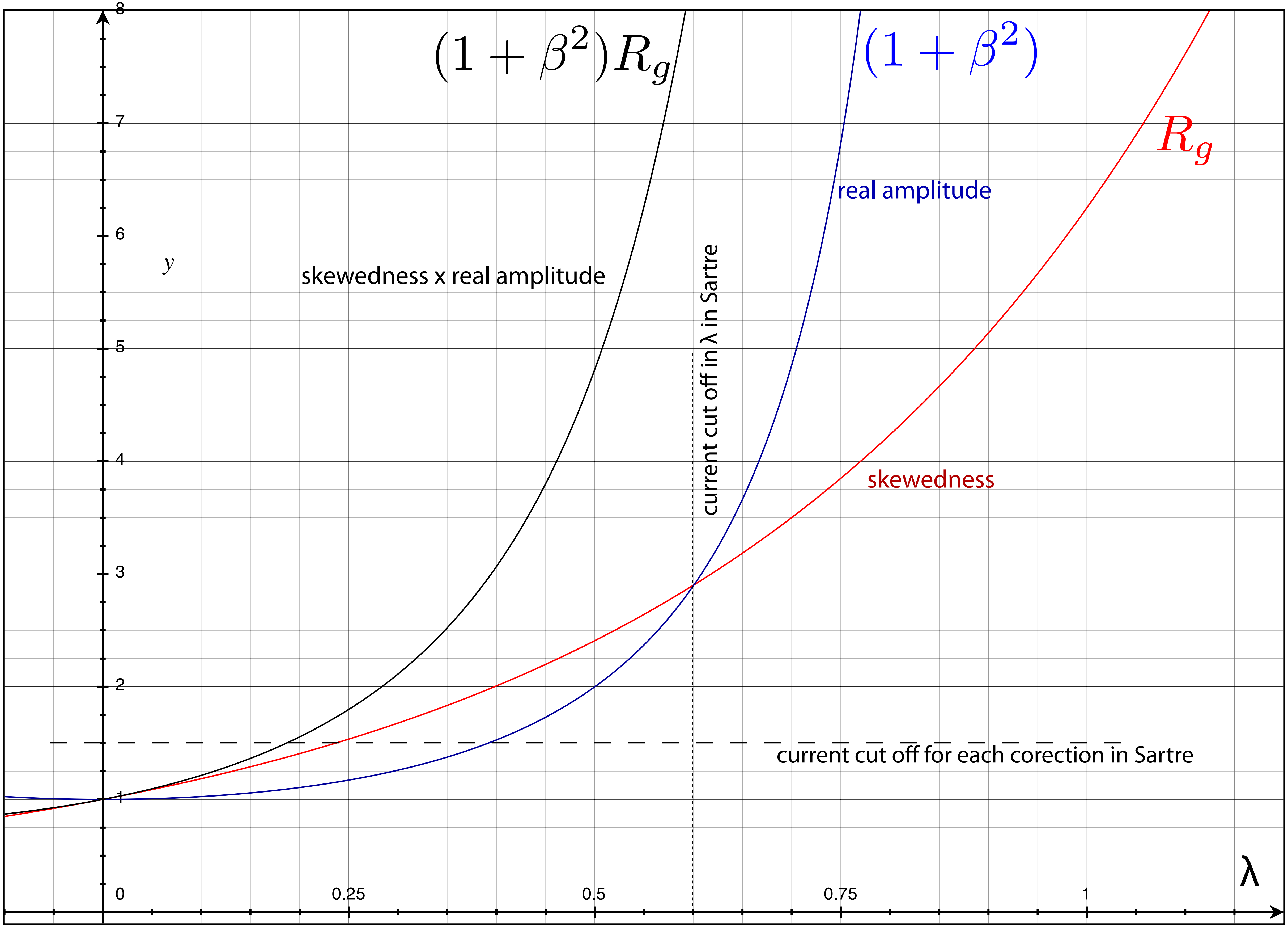
The ten commandments of event generation:

1. Thou shalt never believe event generation is easy
2. Thou shalt always cover the whole of phase space
3. Thou shalt never assume that a jet is a parton or a jet
4. Thou shalt never double-count emissions
5. Thou shalt always remember that an NLO generator does not always produce NLO results
6. Thou shalt always be independent of Lorentz frame
7. Thou shalt always conserve energy and momentum
8. Thou shalt always resum when NLO corrections are large
9. Thou shalt not be afraid of parameters
10. Thou shalt only have nine commandments of event generation

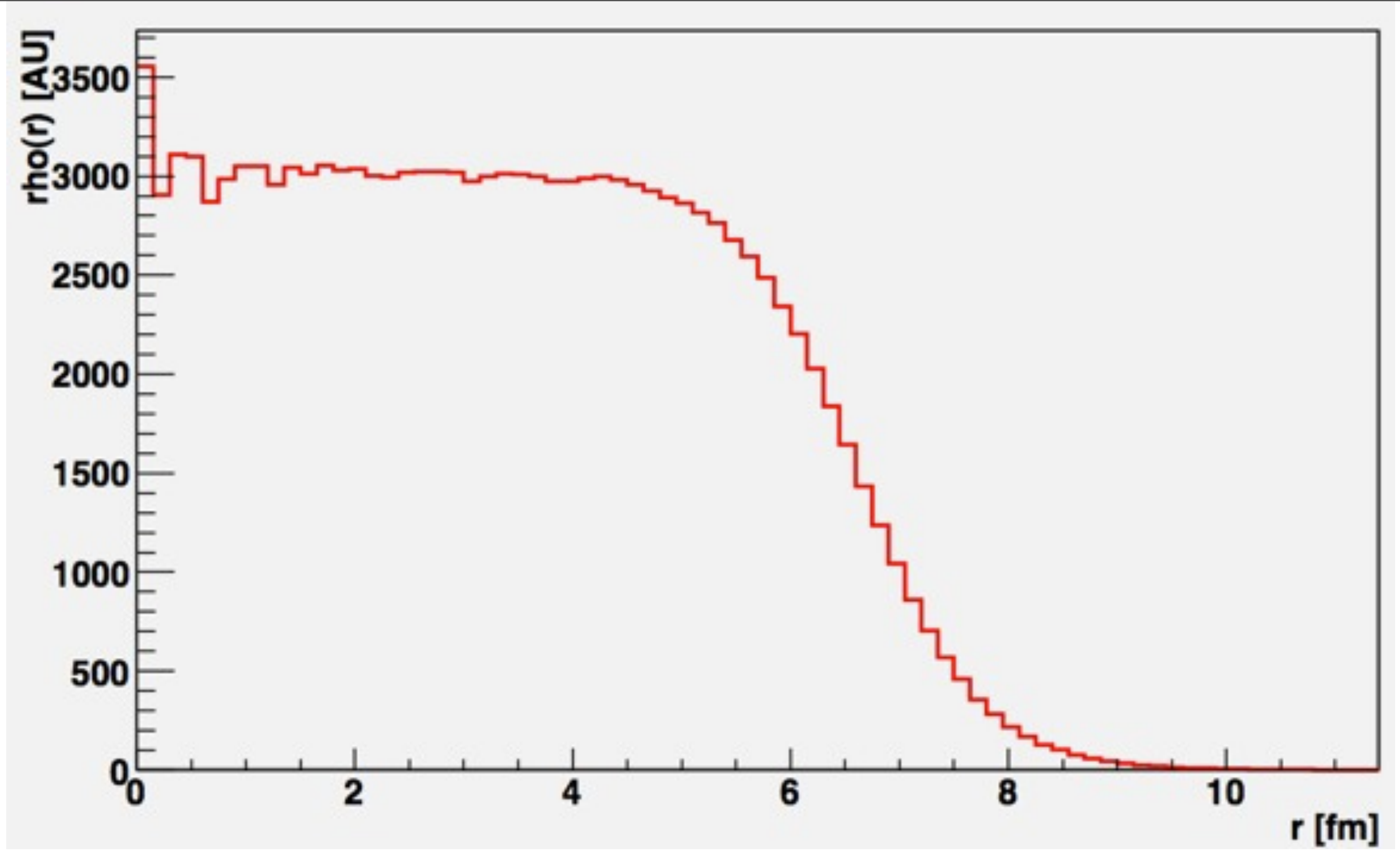
By Leif Lönnblad

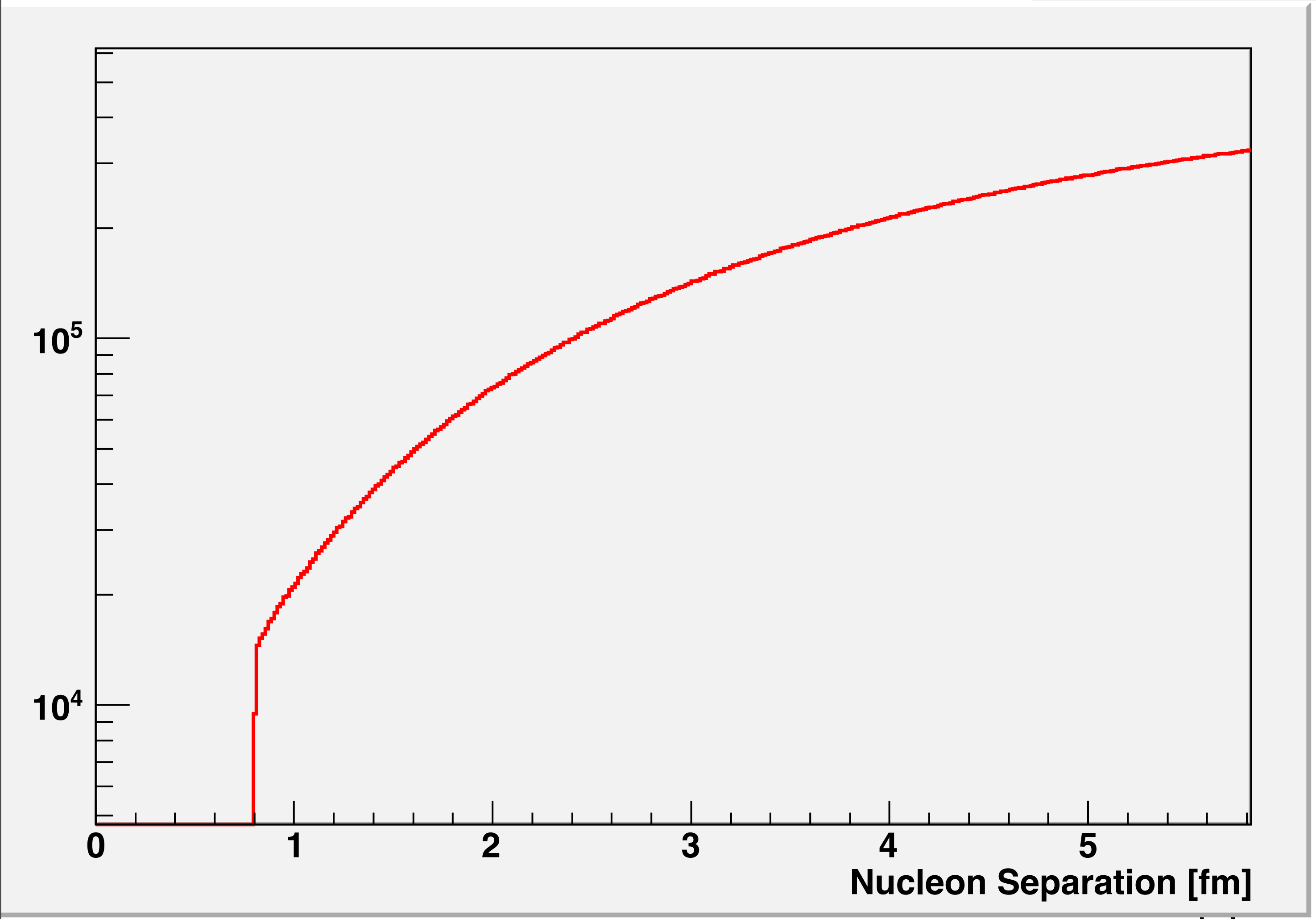
How Sartre works





$(1+\beta^2)R_g$
$(1+\beta^2)$
R_g
real amplitude
y
skewedness x real amplitude
current cut off in λ in Sartre
skewedness
current cut off for each corection in Sartre
λ
0
0.25
0.5
0.75
1
1
2
3
4
5
6
7
8


rho(r) [AU]
3500
3000
2500
2000
1500
1000
500
0
0
2
4
6
8
10
r [fm]


10^5
10^4
0
1
2
3
4
5
Nucleon Separation [fm]